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AN ECONOMIC STUDY OF WAVE POWER

by

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Abstract

This report summarises the need for an alternative energy source and proposes an electrical scheme suitable for the transmission of wave power generated electricity 20km to land by submarine link. The capital cost, unit cost and reliability are studied with a view to assessing the overall economic viability of bulk electrical generation from wave power.

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1. Introduction

1.1 The Need for an Alternative Energy Source

The limitations for any source of energy are the renewability of supply and the technical and economic feasibility of exploitation. All energy sources currently used on a large scale suffer from one, or more, of these limitations. It is however the finite nature of these sources which causes most concern.

At present, although fossil fuels supply most of the world's electrical energy requirements, nuclear fuels are taking on an increasingly large role. The cost of making an accurate survey of the remaining reserves of these fuels would be enormous. Nevertheless, the formulation of current energy policies which determine the future exploitation of fuels requires some estimate of the availability of suitable, economically recoverable, reserves. A study of some recent estimates of the world's reserves of fossil fuels, and of uranium, will reveal the reasons behind the present concern for an alternative source of energy: that is, one which is not currently being exploited.

In 1973 it was estimated that the world's gross coal resources totalled 15.2×10^{12} t [(1)] (Table 1.1). This figure is made up from known reserves plus inferred deposits. Previously, in 1968, the World Energy Conference identified over 8.8×10^{12} t. These figures show remarkable consistency. Assuming that 50% of these reserves can be economically recovered, this figure represents 1500 times the 1970 world output of about 2.9×10^{9}t of coal. Various spokesmen for the industry have tried to put this figure into realistic perspective [(2)] :

"Assuming that world coal requirements will increase by 5% per annum until the end of the century .... sufficient reserves would still be remaining to sustain output at the level of year 2000 for over 300 years." Although this appears to represent an abundant supply of coal, reference to Table 1.1 will show an unequal distribution of reserves which could result in severe shortages in some areas at a fairly early date.

The major drawback of coal as a fuel is evident in the energy policy of the United States. With abundant reserves readily available, the United States is reluctant to revert to coal because of the environmental aspects of using high sulphur content deposits. Factors such as uncertainty in supplies of low sulphur coal; high cost of removal of sulphur from coal or effluent gases; health and safety regulations affecting the mining of coal and the recurrent transport problems make the future use of coal a less attractive proposition than the bare resource estimates first suggest.

The role of oil for future electrical generation is more critical than that of coal. Recent estimates (1972) favour a figure of about 1900×10^9 barrels ($300 \times 10^9 m^3$)(3) as a measure of the world's ultimate recoverable resources. It may also prove possible to extract a further 200×10^9 barrels ($32 \times 10^9 m^3$) from the same sites by using improved techniques. The price rises of 1973 and 1974 have stabilized world demand at about 20×10^9 barrels ($3.2 \times 10^9 m^3$) per annum. At this level of demand these reserves will last for 105 years but only 40 years at a growth rate of 4%.

More reserves of oil will almost certainly be found. Also, as the price of oil from present sources increases along with, indeed ahead of, the price of other fuels, those reserves already known, but previously considered to be uneconomic, will be opened up. Notwithstanding this, the situation is fast becoming critical:

"Production rates have now reached the level at which cumulative production for the decade represents a substantial proportion of the world's estimated recoverable resources and it is obvious that such growth rates can only be supported for a limited period."(3)

The world is not running out of oil, but future policies influencing the usage of oil reserves must be considered at length and with great care.

Of the three fossil fuels discussed here natural gas reserves are the most difficult to quantify. This is because of differences in definitions, energy values, composition, etc., between sets of data produced by different countries. Also, natural gas is a new and expanding industry with policies relating to its development varying throughout the world. Mismanagement of resources in the United States has led to a situation of severe supply difficulties in the immediate future. This in turn has influenced the policies of other countries. In particular, natural gas supplies in the United Kingdom are already rationed and the development of the market is very closely monitored.

The present world reserves of natural gas are estimated to total $72.4 \times 10^{12}\ m^3$ - equivalent to 440×10^9 barrels of oil. If, however, the reported U.S.S.R. reserves are exploited this is expected to produce some $86 \times 10^{12} m^3$. These figures, together with the changing policies of the world and the extremely uneven distribution of reserves, only help to emphasise the uncertain position of natural gas in future energy supplies for the world.

Nuclear fuels present a similar problem to that of natural gas. The extent of the available resources is known to a certain degree but there are many factors which will influence the demand on these resources. The total amount of uranium available, to a depth of about twenty kilometres, is probably of the order of 10^{14}t. This figure includes sources of such low grade, containing 0.001% or less, that they must prove uneconomic. A conservative estimate of the reserves is given in Table 1.2. Total reserves to a price of 60$/kg of U_{238} amount to 4.05×10^{6}t. Exploration for the metal has not been intensive and there are expected to be further substantial economically recoverable deposits.

The principal factor affecting the exploitation of uranium resources will be the extent of development of different types of reactors. One extreme would be total commitment to advanced thermal reactors supplying the world's 1000GW of demand. Annual ore consumption would be 1.2×10^{5}t and present reserves up to 60$/kg of U_{308} would last until about 2010. On the other hand, if commercial fast reactors were to be introduced in 1985 and expanded until 2000, after which all existing thermal and fast reactors were replaced by a notional, molten salt breeder reactor which achieves 100% penetration by the year 2025, the nuclear programme would be free from further dependence on mined uranium.

The shorter term (the next twenty to thirty years) is the real problem for uranium ore supplies. With approximately 500GW of thermal reactors installed or planned and long lead times from discovery to extraction of uranium, severe strain will be placed on present suppliers. Fast breeders will have no effect on supplies within this time scale.

There is, therefore, little hope of satisfying future electrical energy demands from present sources. Supplies of both oil and natural gas must be geared to premium price markets and this automatically excludes large volume, low efficiency steam raising power stations. It would appear that the declining role of coal must be stopped (even reversed) if we are to survive the 1980s with a comfortable margin of safety. Nuclear power, our present hope for the future, depends on the commercial development of new types of reactors, as those installed to date are already starting to strain their fuel resources. A logical approach to the problem requires the investigation of all possible options. Results of work with fast breeders in France and Britain are not discouraging. Also, progress with fusion reactors, although inevitably not proçeeding as quickly as anticipated, is being made. It is, however, rather presumptuous to put all of our eggs in the nuclear basket - there may be other feasible options.

1.2 Possible Alternative Sources of Energy

There have been many suggestions for extracting power from renewable sources. These are developed ultimately from either the earth, moon or sun. Power from the sun can be considered as infinite. We can tap this source without affecting its long or short term future output. If it were to "go out", then the world's demand for electricity would soon reduce to zero. Using power from the moon in the form of tides would also appear to be relatively secure. In contrast and despite the opinion of many people, geothermal power is finite. Although it may be in abundant supply it must inevitably suffer the fate of fossil fuels - an end to its reserves.

1.2.1 Solar Energy

Direct conversion of solar energy by solid state devices has proved successful for powering small machines and instruments especially on satellites. Earth bound collectors receive radiation of much lower intensity and this coupled with a maximum theoretical efficiency for such devices of 25% makes the viability of large scale generation doubtful. (It is popularly quoted that it takes fourteen years for a solid state solar cell to recoup the energy used for its manufacture.) Geostationary satellites beaming power to Earth via microwaves have been proposed. The capital cost, maintainance cost and reliability of such a scheme are almost certainly prohibitive.(5)

Direct conversion of solar energy by focusing the Sun's rays onto a boiler is also possible. By concentrating the radiation from just under two square kilometres area, the temperature of the boiler may be raised to $2000^{o}K$. Another proposal utilizes the greenhouse effect to raise the temperature of a mixture of molten salt and potassium contained in pipes with selective coatings. Even under near ideal conditions almost one tenth of the area of Arizona would be required as a collection area in order to supply the demand of the United States in 1970.

1.2.2 Biological Conversion

Wood has been a source of energy for Man almost since his time on Earth began. Today, it is still possible to supply all of his electrical requirements by burning wood. In Britain, however, this would require devoting 45% of the land area to growing trees and a further 20% to husbandry. With crop-bearing land at a premium throughout the world, it would be hard to justify the use of land in this way. On the other hand, countries with tropical climates, lower population densities and vast areas of unproductive forest may find such a scheme more than attractive.

1.2.3 Windpower

An equally subtle manifestation of solar energy is the wind. Winds are caused by the differential heating of the Earth's surface by the Sun. This difference is most pronounced between land and sea giving rise to reasonably predictable coastal winds. Man's attempts to harness this source of energy have spanned centuries. Although successfully producing electricity on a small scale his success rate for large scale generation has been negligible.

Windmill designs fall into two classes: horizontal or vertical axis. The largest of the traditional horizontal axis design was the 1.25MW Smith-Putnam machine. This was built in 1941 and stationed on a hill in central Vermont. The tower was 30 metres high and the blades 53 metres across. Shortly after entering commercial operation, one of the blades was destroyed in strong winds and the project was ended. Until recently, vertical axis machines have been less popular because of their lower efficiency. The National Research Council of Canada have designed a windmill which shows some improvement in efficiency over other vertical axis machines.(5) It has blades with a symmetrical aerofoil section which bow out to a diameter of 4.25 metres. The electrical output is 1kW in a 6.6ms^{-1} wind, rising to 8kw in a 13ms^{-1} wind, Beaufort Force 4 and 6 respectively.

Horizontal axis machines have a high capital cost that is attributable to the factor of safety which must be built in if the equipment is to survive gale force winds. In such conditions the bending stresses at the roots of the rotors and on the tower are enormous. It is possible to feather the rotors in such conditions but this must weaken the structure at its most critical point. At the same time, the "cut-in" wind speed must be as low as possible in order to smooth the fluctuations in output. Vertical axis machines have many advantages for they do not need to be turned face to the wind, need only a small support tower, deliver their power close to ground level and have much reduced bending stress.

The difficulty of harnessing the wind's energy reduces to a problem of energy storage. Although many large scale storage mediums have been proposed, none (other than pumped-water storage) have yet been proved.(4) Until effective storage can be incorporated into a wind power design the low load factor associated with unreliability of supply will make the cost prohibitive.

1.2.4 Tidal Power

Tides are generated from the varying gravitational fields produced by the relative motion of the sun and moon. Operating on a fourteen day cycle, the usual tidal variation around the world is about one metre. Certain geographical situations can, however, give rise to tidal variations suitable for generation. Britain has several possible sites including the Severn Estuary. The C.E.G.B. have modelled several of the proposed schemes for this site. By using different modes of operation, their estimates of the available power vary from 2500MW to 5000MW.

This upper limit represents 10% of Britain's demand, at an estimated construction cost of £1500 million. With no fuel costs and the possible benefits to shipping and communications such a scheme appears to be attractive. There are, however, many problems. The loose material in the estuary bed makes barrage construction difficult and leads to silting which blocks turbine entry ports and shipping lanes. Due to long construction times, interest charges will raise the overall capital cost and the output may more realistically represent somewhat less than 10% of demand by the completion date.

One of the best known tidal schemes outside the U.S.S.R. was built at the Rance Estuary in France in 1966 with an installed capacity of 240MW. Situated at the most favourable site in Western Europe, the scheme has worked satisfactorily apart from difficulties with silting. The future of tidal power requires a greater appreciation of the environmental impact in the surrounding area. The experience gained at Rance should prove invaluable in assessing these problems.

1.2.5 Geothermal Power

Geothermal power can be extracted from two types of well: the "conventional" wet well and the dry well. A few sites around the world generate electricity from sources of hot water near volcanoes. An Italian scheme at Larderelo, started in 1904, now has a capacity of 370MW. One site at Wairejei in New Zealand and another at The Geysers in

California, have capacities of 290MW and 400MW respectively. In addition to being very localised, the power available from the wet geothermal sources is limited: some 60,000MW per annum for fifty years in anticipated.(6)

The dry well depends on a high temperature gradient through the crust of the Earth. Two holes are drilled vertically downward until a suitable temperature of rock is reached. Hydrostatic pressure is used to fracture the rock and sand is pumped down to hold the fissures open. Water is circulated from the lower hole through the fracture to the upper hole and is withdrawn as hot water for generation. These techniques are well established in the oil industry.

Although suitable sites for dry wells are more abundant, the necessary higher temperature gradients tend to be found only at sites of recent volcanic activity. A project scheme at Los Alamos, New Mexico, working with a temperature gradient of 100 Kkm^{-1} near the surface, hopes to extract some 250MW of heat. Lower thermal gradients mean that the bore holes must be drilled deeper. In the United Kingdom, a temperature gradient of 30 Kkm^{-1} (such as is found in parts of Cornwall) could produce electricity at £300 to £600 per kilowatt.(5) Although the lower figure is competitive with nuclear power, the experience to be gained at Los Alamos is needed to quantify the problems and costs more precisely.

1.2.6 Wave Power

The ocean acts as a large collecting and concentrating medium for the diffuse power of the wind. Wave power is therefore ultimately derived from the Sun. Since there is no associated fuel cost the efficiency of a wave power scheme will determine its size and cost. Many designs for large scale power extraction have been proposed but reasonable efficiencies have only recently been achieved. In particular, Salter (1974) at the University of Edinburgh has achieved efficiencies of more than 50% over a bandwidth of 2 to 1. A design by Sir Christopher Cockerell has achieved efficiencies of 44% over a narrower bandwidth.

Data from the weather ship "India" in the North Atlantic suggests that the average power available throughout the year is 70kW per metre of wave front. A barrage some 720km in length could supply the present United Kingdom demand for power. The economic viability of Salter's wave power scheme (for generating electricity to transmit by cable to shore) is the subject of this report.

1.3 Brief Details of Wave Power Scheme.

The device used by Salter to extract power from waves is known as a duck;[(6)] see Figure 1.3.1. The leading edge of the duck absorbs the energy of an incident wave (as would a flat plate). The back is rounded so that none of the absorbed energy is transmitted to the water on the lee side. The optimum contour of the leading edge is frequency dependent and so must be tuned to the anticipated average frequency of ocean waves. The approximate size of a single duck is envisaged as being about ten metres in diameter by twenty to forty metres in length. The construction material would be concrete and the physical interconnection between ducks is by means of a semi-rigid backbone.

This study is based on a conceptual wave power plant designed to generate 400MW of electrical power. This is a convenient size of electrical and civil plant to form a "unit cell" of a larger integrated network which is in line

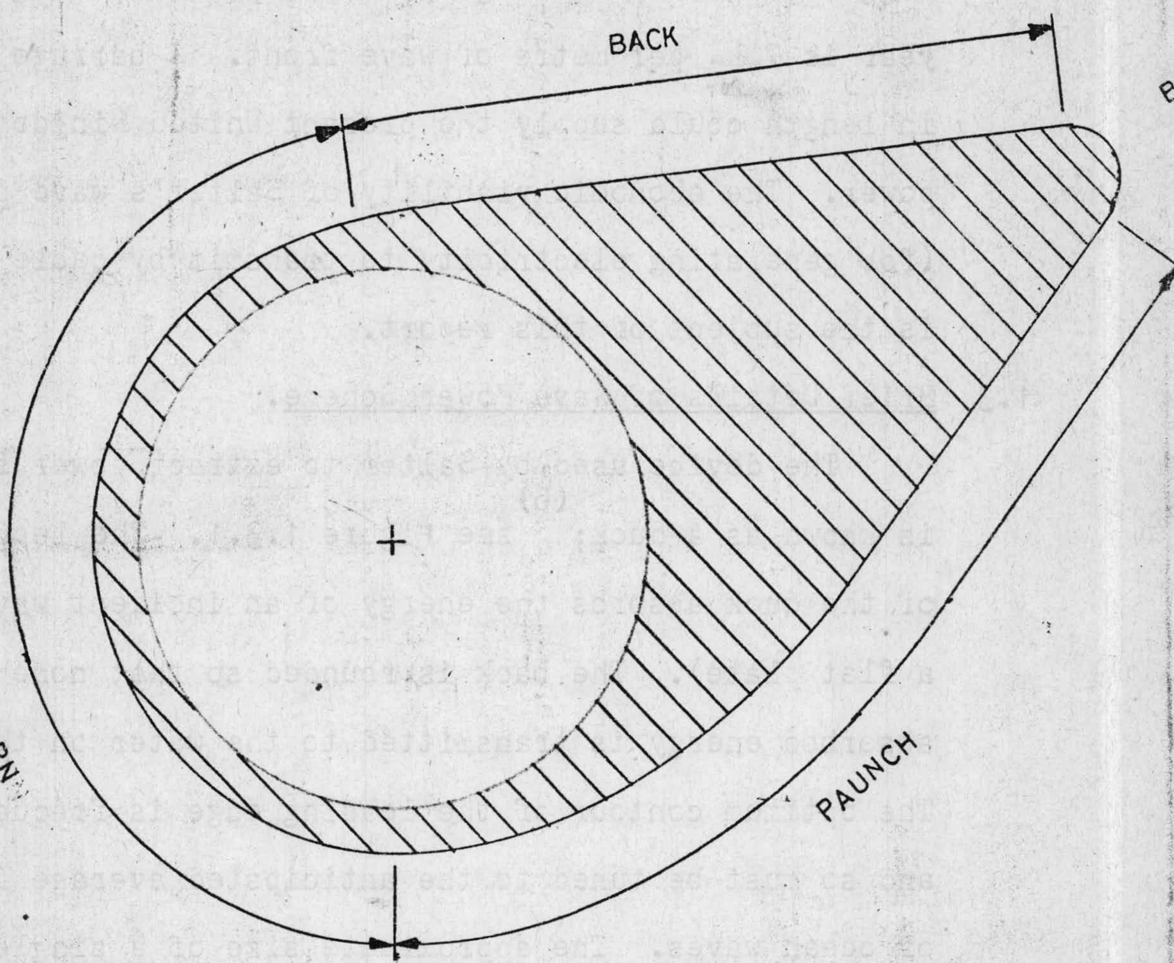

FIGURE 1.3.1 ANATOMY of a DUCK.

with the whole modular concept of the design. The magnitude of power output is also sufficiently large (about one-quarter the size of a modern conventional land-based power station) to give reasonable practical comparisons. The length of duck string involved in a scheme of this size would be approximately 8km, with about 130 connected ducks. A suitable site for such a scheme lies some 20km off the west coast of the Outer Hebrides. Here the average annual wave size is amongst the highest around our coastline. Also, the area is conveniently remote from any major shipping lanes.

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Electrical generation would take place inside the hollow ducks. The motors, generators, transformers and other associated equipment would be housed near to the internal perimeter so that their combined inertia may be utilised to best advantage (by maximising the total rocking inertia). The electrical power would be fed by flexible low voltage cables to a processing station on the sea bed. This processing station would step up the voltage to a suitable value for transmission to shore. If d.c. transmission were to be used then rectification would also take place within the station.

2. Details of Electrical Options

No one scheme can claim to be the best and at this early stage a divergence of ideas will provide a pool of possible options. However, in order to carry out an economic study, a likely scheme must be fairly well defined. Such a scheme is proposed in this report but wherever appropriate, optional systems are suggested.

2.1 On-Duck Scheme

A schematic diagram showing the on-board power flow is shown in Fig. 2.1.1. The option of a.c. or d.c. does not have a great influence on the on-duck equipment because a.c. generators will almost certainly be chosen: d.c. requires frequent inspection and maintenance of commutator brushes and is limited in unit size. The reliability and performance of brushes depends on many factors (atmospheric environment; hardness of material; generating voltage, current and speed etc.) but bimonthly inspection would be required. The remote and hazardous nature of the plant environment makes such a schedule impossible. Thus generation would be by synchronous machines. If d.c. transmission to shore were to be used, then some generator interconnections and transformer windings may be altered.

The scheme assumes the existence of a rotating prime mover within each duck, governed by a torque limiter to protect the motors and electrical equipment from damage when the incident wave power density is greater than the design figure. It will become apparent later that in order to achieve a high efficiency the torque limiter would have to operate for most of the time. Breaking waves are likely to cause structural and mechanical damage. In this

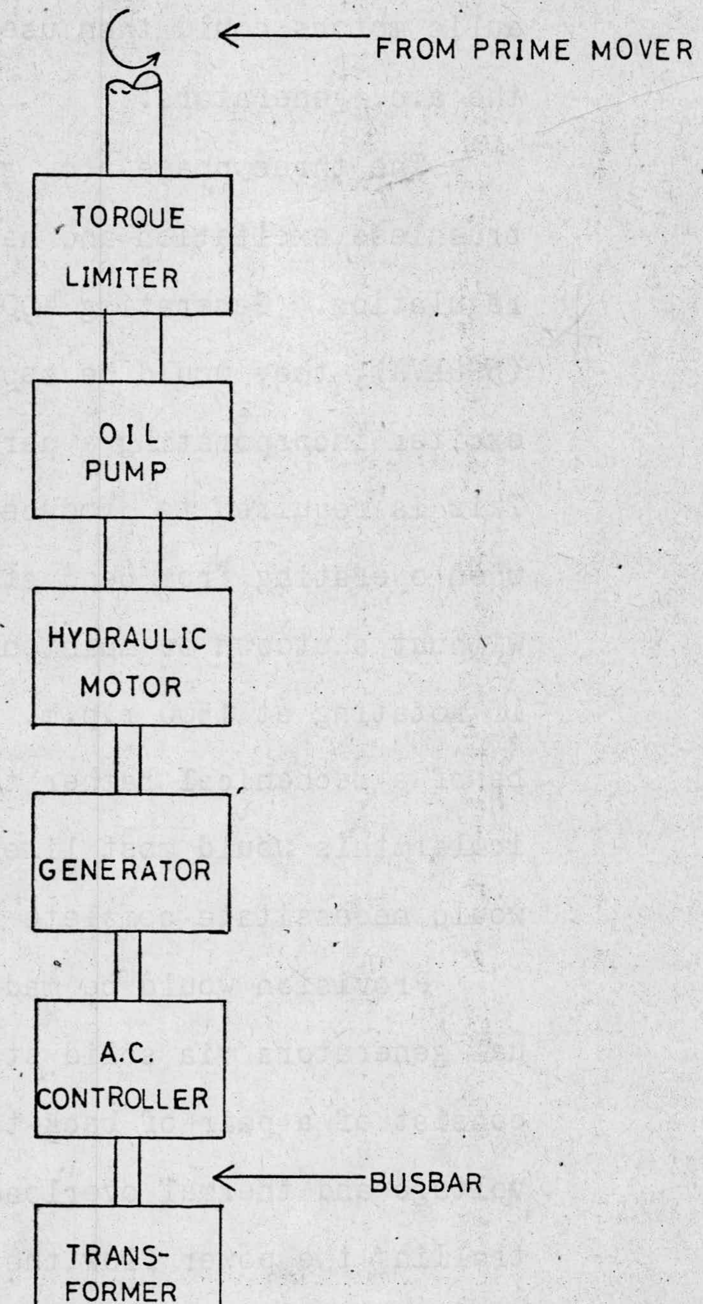


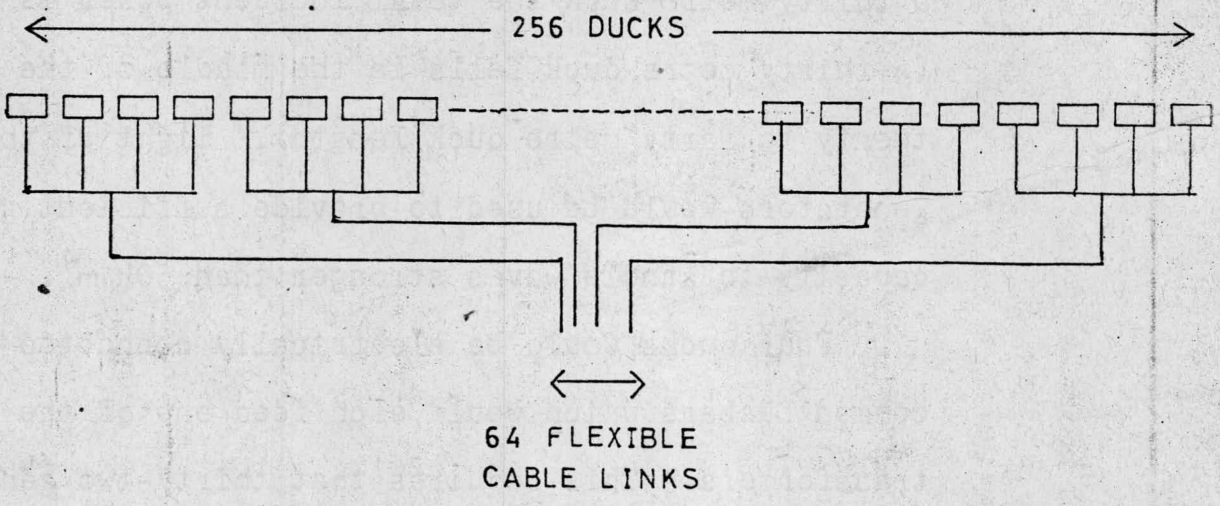
FIGURE 2.1.1 Power Flow On-Board Duck.

event some more effective means of attenuation would have to be provided. The prime mover would drive an oil pump and the storage of the compressed oil could act as a buffer to help even out the minute to minute fluctuations. Hydraulic motors could then use the compressed oil to drive the a.c. generators.

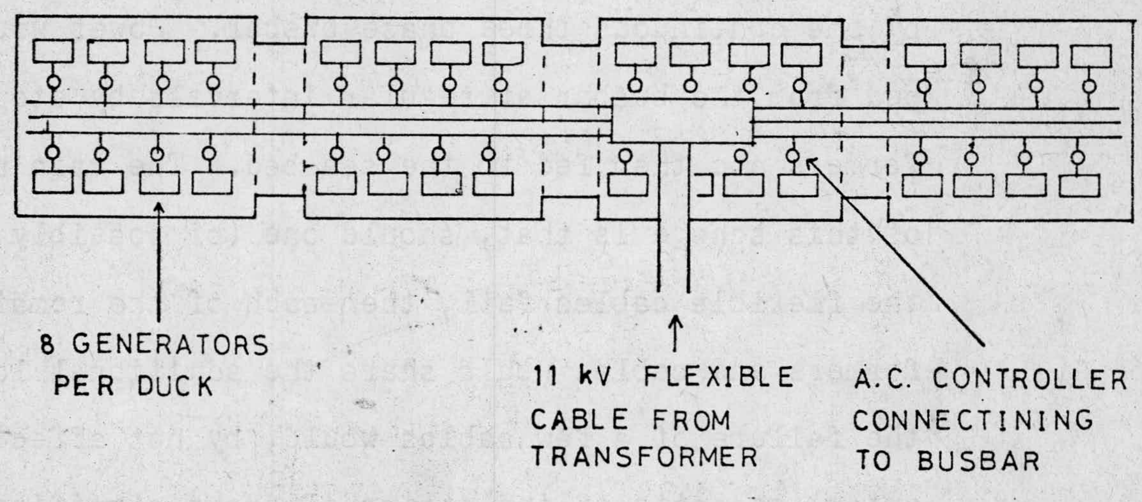
The three phase a.c. generators envisaged would use brushless excitation and have built-in automatic voltage regulation. Generating 400kW at 415V and 0.8 power factor (500kVA), they would be supplied complete with a pilot exciter incorporating a permanent magnet a.c. generator. This is required to produce the necessary d.c. excitation when operating from dead start. These machines could operate without shutdown or maintenance for over twelve months. If rotating at 1500 r.p.m. their most likely fault would be of a mechanical rather than electrical nature. In particular this would most likely be a bearing failure which would necessitate complete shutdown of that set.

Provision would be made for the selection of individual generators via solid state a.c. controllers. These consist of a pair of back-to-back thyristors with overvoltage and thermal overload protection. As well as controlling the power flow the devices would replace normal circuit breaker protection. The three phase output from each generator would be fed to busbars. The busbars feed a series of onboard step-up transformers distributed at points along the string of ducks. The power would then feed via flexible cables to a processing station on the sea bed.

The proposed scheme (Fig. 2.1.2) uses an average



(a)



(b)

FIGURE 2.1.2 Proposed Scheme. (a) Duck String. (b) Interconnection of Four Ducks.

incident wave power density design figure of $50kWm^{-1}$, the choice of which is explained in section 3.1.1. Hence for a thirty metre duck the total incident power is 2.5MW. (A thirty metre duck falls in the middle of the proposed twenty to forty metre duck length). Eight of the proposed generators would be used to provide sufficient generating capacity to handle waves stronger than $50kWm^{-1}$.

Four ducks would be electrically connected by the common busbars which would each feed one of the step-up transformers. This requires that thirty-two generators be synchronised. The transformer would be 415V/11kV and rated at 16MVA. 11kV would therefore be the required size of flexible cable for power transfer to the sea bed.

Many possibilities of on-duck schemes are available. For example, it may be possible to connect the entire barrage by one continuous three phase busbar. Power would be tapped from the busbar at regular intervals by step-up transformers and then fed to the sea bed. The main advantage of this scheme is that, should one (or possibly more) of the flexible cables fail, then each of the remaining transformers and cables would share the additional load. Thus the failure of a few cables would, by not affecting the output capacity of the string of ducks, significantly increase the reliability. Possible difficulties arise with this scheme in connection with:

(a) the stability of the generators:- With waves approaching the barrage at an acute angle, neighbouring ducks may be 90° out of phase. This results in some generators generating and some nearby generators motoring.(8)

(b) the stability of the rectifiers:- When a.c. rectification occurs the d.c. is not smooth but has a ripple superimposed on the d.c. For a six pulse rectifier arrangement the ripple frequency is 300Hz. A twelve pulse arrangement would give a smaller ripple amplitude and the frequency would be 600Hz. This is preferable and can be obtained by arranging the transformer secondaries alternately in star and delta.

(c) the rating of the transformers:- This would have to be higher than under normal operating conditions. Costly redundance would therefore be built in. Naturally, the same comments apply to the flexible power cables to the sea bed.

Another possibility would be to rectify on-board. This could be done at either the generating voltage or after the step-up transformer. The benefit of this would be to have all the rectifiers on the surface and hence more accessible. Little more than cable jointing would be required on the sea bed.

2.2. Processing on the Sea Bed

To prevent ingression of the sea water the station would have to be perfectly sealed. A suitable technique is already developed for use with metal clad SF_6 substations. In fact, SF_6, because of its electrical properties (9) would be ideal for raising the internal pressure above that of the external. This would be required in order that any small leaks would be of SF_6 to the sea. The contents of the station are principally determined by the choice of a.c. or d.c. transmission.

An a.c. scheme would require a common busbar fed by the power cables from the ducks. The busbar would be tapped by a three phase step-up transformer producing the required transmission voltage; probably 275kV.

A d.c. scheme would require the connection of the incoming three phase supply in series as shown in Fig. 2.2.1. This configuration would produce the high voltage levels needed for effective d.c. transmission. The number of units connected in series would depend on the required transmission voltage and the voltage level of each rectifier. Any single unit may be omitted by closing the by-pass switch.

Concerning both schemes, the grouping of four ducks together (as in the proposed scheme) would simplify the cable arrangements to the station. The switching gear and internal wiring of the station would also be much reduced (Fig. 2.2.2). The system would however be less flexible than if an 11kV cable were to be run from each duck. In that instance any single duck, or number of ducks, could be completely isolated for maintenance or in the event of a fault. With grouping, although each generator may be isolated via the circuit breaker and a.c. controller, the smallest number of ducks which may be disconnected from the station is four. The simplified processing station may, therefore, have an adverse affect on reliability and availability. (The continuous busbar scheme mentioned in 2.1 would avoid this problem).

2.3 Transmission Ashore

Transmission ashore will be by a.c. or d.c. There are two bases for decision: one technical and the other economic. Obviously the two are not independent but there may be one single overriding reason, technical or economic, which precludes one type of transmission scheme. A discussion of

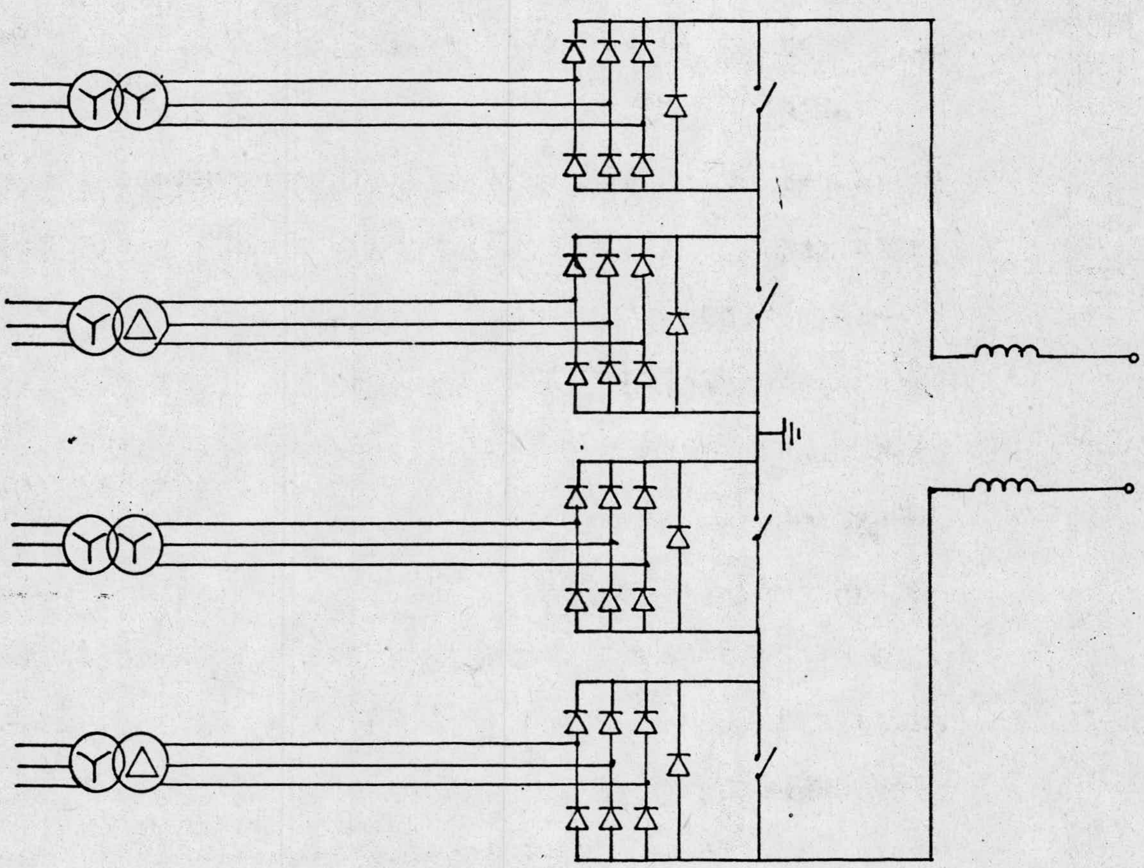


FIGURE 2.2.1 High Voltage Series Rectifier Arrangement.

the technical feasibility of both a.c. and d.c. schemes is given in reference 10. The economic basis for decision forms a later part of this report. It is, however, appropriate to outline the main factors of both bases here.

Power transmission at high voltages is more efficient by d.c.[11] The a.c. losses are caused by having to charge the cable capacitance twice every cycle. Quadrature charging current therefore appears in a.c. cable or line. The voltage withstand levels of insulation are proportional to peak voltage. In an a.c. line, the power transmitted is proportional to the root mean square (r.m.s.) voltage whereas in d.c. the peak and r.m.s. voltages are the same. This means that more power, at a higher voltage, may be transmitted by d.c. Problems arise should the whole country be supplied from d.c. transmission. There is a demand for quadrature current from the grid system and special arrangements would have to be made to meet this.[10]

For the technical reasons mentioned above (lower breakdown insulation and less copper), a d.c. line transmitting the same power as a comparable a.c. line is cheaper. The terminal equipment associated with d.c. transmission (basically rectifiers and inverters) is more costly than the a.c. equivalent equipment. The breakpoint for a financial decision on a.c. or d.c. occurs when the savings from using the cheaper d.c. line balance the extra cost of the d.c. terminal equipment. It is, therefore, common practice to use d.c. for larger transmission distances.

The proposed offshore distance for the barrage of ducks (20km) is near the breakpoint. For this reason, both the technical and economic aspects of a.c. and d.c. transmission ashore must be studied. A discussion of the technical considerations is to be found in reference 8, however, a brief description of two possible schemes follows.

Transmission ashore by a.c. is most likely to be by three phase cable. At 275kV the conductor cross-section would be 500mm^2. Short a.c. submarine links are fairly common and no special problems other than handling the large diameter cable are envisaged.

Since d.c. submarine links are also fairly common a great deal of experience has been gained in this field.[12,13] The system would use ±250kV transmission cables and the earth and sea as a return conductor. There is also considerable experience in the use of earth electrodes.[10,14]

There are many possible routes for the transmission line but all would require grid reinforcement on the shore. An economic appraisal of some specific routes is included in Chapter 3 whilst the reliability and availability of these routes is discussed in Chapter 5.

3. Capital Costs

Without specifying a precise scheme an exact costing can not be achieved. Hence, the proposed scheme can only be used as an illustrative example to provide an order of magnitude estimate. As an inflationary economic climate makes year old prices out of date and unrealistic, most prices have been quoted on an informal basis. The costs from each section are tabulated for easy reference.

3.1 Costs Onboard the Barrage (Table 3.1.1)

3.1.1 Civil Cost

The civil cost of the duck is determined by its physical size. This figure would include the jointing between ducks to form a string and the provision of foundations for internal generating equipment and auxiliaries. The optimum size would be a function of the design figure used as the average wave power density. An important parameter in determining this is the load factor of the duck. The load factor is defined as the actual energy delivered from the scheme divided by the energy delivered if the scheme were operating continuously at maximum output. From inspection of the whole year output for duck diameter curves, (see Fig. 3.1.1) it would appear that a 10m. diameter duck scheme designed for $50kWm^{-1}$ is near an optimum. From the curves, this would give a whole year mean power output of $28kWm^{-1}$; a load factor of 56%. A larger duck diameter designed for $50kWm^{-1}$ would improve the load factor but not by a significant amount considering the extra capital cost. The incident wave power density varies from zero in flat calm to about 1MW per metre in stormy seas. However, to design for a high incident wave power density would be to build in much

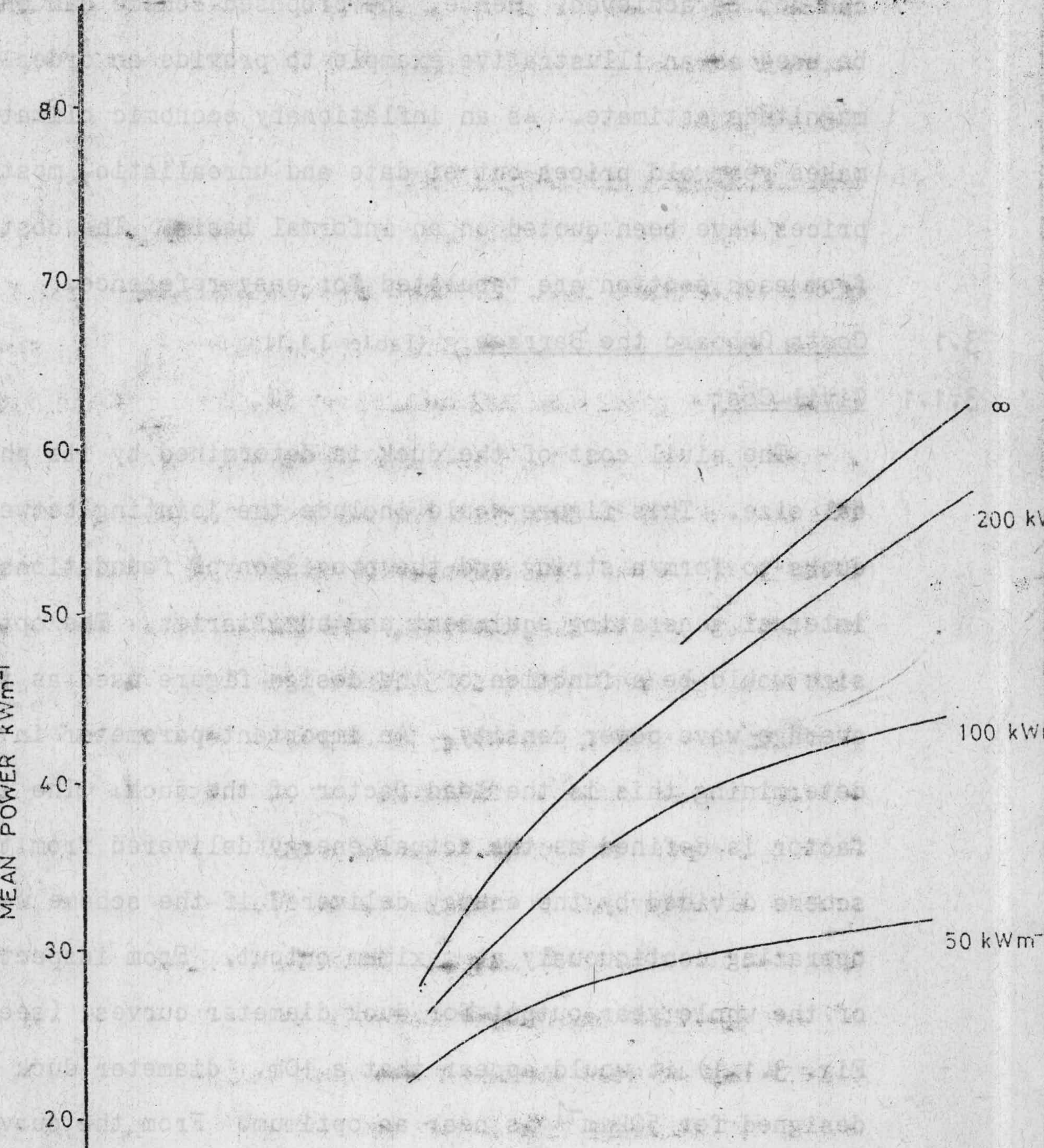


FIGURE 3.1.1 Whole Year Output for Duck Diameter

redundancy which would adversely affect the load factor.

The estimated capital cost per duck is about £500 per metre length and per metre diameter.[10] For the proposed barrage scheme of total length 8km this would amount to £40,000,000.

3.1.2 Cost of Motors and Generators

Brief technical details of the proposed generators are given in section 2.1. Further information about their interconnection etc., is given in reference 8. The cost of a single generator was quoted as £2,600.[15] With eight generators in each duck and 256 ducks this comes to £5.4M. The duck would be designed for an incident wave power density of $50kWm^{-1}$ and this means an incident design power of 1,600kW per duck. However, the installed generating capacity proposed above is 3,200kW per duck. Now a certain surplus generating capacity is required to deal with waves stronger than $50kWm^{-1}$. Although (as mentioned in section 2.1) a torque limiter is used as protection, the system would suffer a reduction in efficiency if this were set too near the precise required torque. Notwithstanding this, a factor of two (3,200kW installed capacity to 1,600kW incident design power) may be over cautious and some savings could be effected by reducing this ratio and using fewer generators.

A figure of £5.4M is taken as the cost of generators for the proposed scheme.

The hydraulic motors used would be capable of attaining speeds suitable for electrical generation from oil pressures of 1.4×10^7 to $2 \times 10^7 Nm^{-2}$. These pressures are attainable by using conventional wheel hub motors from slow, heavy vehicles. Each duck would ride on as many as one hundred of these, which would be fitted with seals for marine and submarine applications. The total capital cost of the hydraulic system is estimated at £6,000,000.[10]

3.1.3 Control and Switching Cost

The a.c. controllers mentioned in section 2.1 have been quoted at around £ 2kW^{-1}.[16] One controller would be required for each generator. The capital cost involved would be therefore £0.8M. This price includes the protection circuit and water cooling accessories which would be supplied with the devices.

The busbars to which the controllers would be connected require to be flexible - at least at the connection between ducks. In fact, cabling may well be used for this. In the extreme, the busbar must be capable of carrying the total installed capacity. The cost of suitable cable would be £0.2Mkm^{-1}[20] and so for the 8km string the total cost would be £1.6M.

3.1.4 On-Board Transformers

The 16MVA transformers cost around £23,000 with an additional £3,000 for neutral earthing resistors.[17] However, the price does include Buchholz protection and oil and winding temperature indicators. For the proposed scheme the on-board transformers would cost less than £1.7M (i.e. one for each of the sixty-four, 4-duck units).

The power would be fed to the sea bed via 11kV cable of total length 20km. The cost of 11kV submarine cable is about £5,000 per kilometre.[18] The armouring around normal submarine cable would possibly make such cable too inflexible for the proposed application. The required cable should be able to flex but remain water-tight. However, £5,000 per kilometre is taken as the best available estimate. At this rate, the capital cost of electrical connection from the duck string to the sea bed would be around £0.1M including termination in the processing station.

3.2 Sea Bed Processing Cost (Table 3.2.1)

3.2.1 Equipment Housing Cost

The starting point for an estimate of the submarine station design is the cost of a metal housing for a 500MVA transformer. This is in the region of £15,000.(17) One of the additional requirements to the normal housing is that it must be made water-tight. This can be done since totally enclosed SF_6 substations are completely sealed. However, the proposed sea bed station has over sixty cable entry ports. It would also be subjected to the corrosive nature of the sea without having the benefit of easy regular maintenance. A factor of seven times, to bring the cost to £0.1M, does not seem unreasonable considering the unique nature of such plant.

3.2.2 A.C. Processing Cost

The a.c. processing plant would basically consist of a 500MVA transformer with high voltage circuit breaker protection (Fig. 2.2.2). The price of the transformer should be around £0.8M.(17) A suitable 275kV circuit breaker would cost £0.3M and its associated protection circuitry about £0.1M.(17)

3.2.3 D.C. Processing Cost

The d.c. scheme would not require a high voltage circuit breaker since power could not be fed back through the rectifier bridge. Therefore, in conjunction with the front-end a.c. controllers, the transformers (on sea bed and on-duck) would effectively be isolated from reverse power flow to them. Cable length should act as sufficient attenuation for transformer faults. D.C. convertors are quoted at around £20kW^{-1} [19] resulting in a capital cost of about 20% of this figure (£2M). The d.c. sea bed processing costs are, therefore, considerably more than a.c. mainly because of £2M for the rectifiers.

3.3 Transmission (Table 3.3.1)

3.3.1 D.C. Cables

D.C. transmission to shore could be via two cables at ±250kV, the current carrying capacity of each cable being 800A. The 1976 price for such cables is approximately £0.2M per kilometre and per pair.[20] (Cable quoted at this price was capable of carrying 1000A). Each pole would be earthed at either end and if the system were balanced (both poles carrying the same current) then the earth/sea as a return conductor would carry zero current. Electrodes in the land and/or sea appear as a capital cost but since anode bars decompose (about 20g per 1000Ah)[10] they also appear as recurrent costs. Depending upon the siting of the d.c. converting station it may prove convenient to make both electrodes sea electrodes. Otherwise, the land based electrode will have to be an earth electrode.[14] The estimated cost of providing these electrodes is £0.5M.[10]

3.3.2 A.C. Cables

A.C. cable would be 275KV three phase. It is difficult to estimate the cost of a.c. submarine cable of this size. An estimate is based on the cost of equivalent capacity d.c. submarine cable (£0.2M per kilometre, from above) and the cost of a similar a.c. land installation (£0.78M[21] per kilometre). The a.c. land installation includes termination costs (as does the d.c. figure) and is assumed to include the cost of wayleaves. The a.c. cable cost therefore lies somewhere between £0.2M and £0.78M per kilometre. It seems appropriate to assume that about half of the total land installation is labour and wayleave cost. This gives a figure of £0.4M. Submarine cable is more expensive than land cable because of higher manufacturing costs and so £0.5M is taken as the cost of a kilometre of a.c. submarine cable.

3.3.3 Cable Laying Cost

It is once again difficult to find present day figures for cable laying. Figures of £75,000 for eight kilometres and £40,000 for two kilometres have been quoted for 11kV or 33kV cables.[18] Two factors must be considered when using these as a basis for estimation of costs for twenty kilometres of 275kV cable. Firstly, a major part of the cost would be the initial hire of a cable laying ship. This would tend to reduce the cost for longer distances. Balanced against this would be the extra hire cost of a larger ship which is presumable necessary for handling the larger cable. Assuming a slight overall saving when laying some twenty kilometres, a figure of £8,000km^{-1} is taken as being approximately correct. (The saving would be greater if many transmission lines for a large scheme were laid at the same time). The same cost is taken for a.c. and d.c.

3.3.4 Overhead Line Costs

The amount of power coming ashore would require a 275kV overhead line of conductor configuration 2 x 400mm^2[8] which costs £61,000km^{-1}.[21] This figure is for a.c. transmission and is now used to estimate the cost of an equivalent d.c. line. Using the cost ratio of a.c. to d.c. cables (2.5 : 1) gives £25,000km^{-1}. This assumes that the tower sizes (and hence costs) are the same which is unlikely. All of the figures in this section include wayleave and termination costs.

3.3.5 Cable and Overhead Line Routes

The most reliable route for transmission of power should minimise the number and length of submarine links which are susceptible to damage from abrasion on the sea bed, ships' anchors, trawling etc. The most promising route from this point of view would be submarine to the Outer Hebrides, across these islands as far as possible by land, submarine to Skye, overland to the mainland and then on to, say, Glasgow. This route would involve some 370km of line and 50km of submarine cable and would require three or four submarine links. To transmit 400MW of power, submarine cable costs would be in the region of £15.3M and £6.3M for a.c. and d.c. respectively (including laying). Overhead lines would be about £22.6M and £9.3M (a.c. and d.c. respectively). Therefore, rounding the total cost of cable and line for this route gives approximately £38M for a.c. and £16M for d.c.

Many routes are possible; the route suggested above passes through areas of rare beauty and opposition to such proposals must be anticipated. By taking a submarine link direct to the west coast of Argyll, this problem would be considerably reduced. To make such a link under 300km of sea and over 100km of land would cost about £158M for a.c. and £65M for d.c.

Unfortunately, the reliability study in Chapter 5 would appear to rule out this possibility. The annual fault rate on a 3000MW, 300km submarine link would necessitate the permanent siting of a repair ship in the area.

3.3.6 D.C. Convertor

The cost of the d.c. convertor is discussed in section 3.2.3 and should come to roughly £8M.(19)

3.4 Review of Capital Costs

The total capital cost would be dominated by the civil cost of the duck and the cost of transmission. The final civil cost of a duck should be determined by its physical dimensions which are in turn dependent on the shape and frequency of the waves. Since the civil cost forms such a large proportion of the total cost, any incremental change in the duck design may produce a significant difference in the total. As well as being influenced by the nature of the seas, the size of the duck would be affected by the policy of operation. For example, it may be decided that since the fuel is free, large diameter ducks could be used to extract as much energy as possible. As explained in section 3.1.1 this would result in an improved load factor over a smaller duck, dependent on the slope of the curves in Fig. 3.1.1. (Remembering that a ten metre diameter duck was chosen as an optimum economic size in 50kWm^{-1} seas, by increasing this to 15 metres the load factor would be improved from 56% to 62%. However, the capital cost of the scheme would be raised from £40M to £60M.) Therefore, although the civil cost estimates may be accurate, since the design and operational policy have not yet been finalised, the total cost would be subject to considerable variation - possibly up to 35% of the capital cost excluding transmission.

Transmission has a great influence on the capital cost not only because of the expense of cables and line but also due to the multitude of possible transmission routes. Indeed, the economic viability of each proposed site may be determined by the transmission costs alone. The longer the transmission distance the more expensive the scheme becomes. As the coastal regions of Britain are high amenity areas and considerable opposition to the erection of large numbers of power lines can be expected, hidden submarine cables may have to be used where overhead line would have been cheaper and more reliable.

Capital cost estimates of comparable a.c. and d.c. schemes are made in Appendices 1 and 2 respectively. It can be seen from these estimates that considerable savings could be made by using a d.c. system. However the additional cost of the d.c. converter equipment must also be considered. The figures shown apply to a site lying between five kilometres and twenty kilometres offshore. Hence within this range (considering the limits of accuracy of the estimates) there is little difference in the capital costs. Above twenty kilometres the economies of d.c. cables make the d.c. scheme increasingly attractive. In particular at distances over 150 kilometres the power out of a 275kV a.c. cable would be minimal because of losses due to high charging currents.[(8)]

The similarity in price of the two schemes leads to interesting possibilities regarding transmission routes. If considerable opposition to large power lines in e.g. Skye, was met, then the only feasible alternative would be the use of a d.c. submarine cable link to side-step such areas. For little increased cost it would be possible to feed the power from the sea bed processing station to a single shore based switching station. The switching station would feed out into the d.c. submarine links. In a larger integrated scheme the power from several strings of ducks could be fed to the switching station on a rota basis. This means that one or two strings of ducks could be serviced or could fail and there would still be one hundred per cent utilization of the costly d.c. transmission link. The reliability of a long d.c. link would be very poor (Chapter 5) and might influence a decision to use a long submarine link, more than the capital cost difference.

A two pole, two conductor d.c. submarine link to the west coast of Argyll would cost of the order of £62M and converter equipment to handle 400MW would cost £10M (from 3.3). Two 8km barrages with processing stations each capable of generating 400MW would cost £106M and a further £20M to carry their output, by separate transmission cables, to the switching station. This system would cost just under £540kW^{-1} - apparently twice the price of nuclear.[5] For a scheme capable of delivering 3000MW to the mainland, eight 400MW barrages would be used. The d.c. link would be capable of handling 3000MW with additional cables laid to improve reliability (Appendix 3).

All of the costs in this chapter so far have been based on the cost per single item of plant. Bulk purchasing for a 400MW station should result in reductions of about 30% for certain items since much of the cost of generators, etc., is in the setting up of a production line. On the barrage an 8% saving could be effected in this way. For a 3000MW installation 30% of the sea bed processing station cost could be saved. It is, perhaps, unlikely that such a large saving could be made on d.c. plant costs but on a 3000MW scale a 10% reduction might be hoped for.

The C.E.G.B. estimate that a plant of capital cost £300kW^{-1} would be competitive with a nuclear station.[5] This target would appear to be attainable for power delivered to a load centre within 400km of the landing point if a.c. or d.c. overhead lines were used for transmission. (Appendix 3). It would appear that the target could not be approached by high voltage d.c. submarine links of 300km. However, there is the possibilty of going to $\pm$ 400kV d.c. as there is some experience of operating at this level.[12]

4. Unit Cost

The unit cost of electrical energy delivered ashore will depend on the load factor of the electrical transmission system. Two possibilities are of interest. The system may be used as a marginal cost saver by reducing the load on coal and oil fired stations. Alternatively, it could be operated as a base-load supply with or without the assistance of a storage scheme. Obviously the mode of operation will affect the unit cost and some estimate is made of this below. Firstly, however, the seasonal variation in unit cost is shown by examining the proposed 400MW scheme.

4.1 Seasonal Variation in Unit Cost

The unit cost varies throughout the year because of the seasonal change in incident wave power density. The variation in mean power output versus duck diameter is shown in Fig. 4.1.1. These curves are derived from the observations of Molison.(22) His results for duck diameters from six to eighteen metres are shown in Fig. 4.1.2.(rear) Using a diameter of ten metres gives duck load factors of 30%, 64%, 76% and 53% for summer, autumn, winter and spring respectively. Estimates of the unit cost of the proposed a.c. scheme for the four seasons and for different electrical load factors are tabulated in Appendix 3. Also included are the estimates for the whole year. Since the capital cost of the proposed a.c. and d.c. schemes are almost exactly the same, the equivalent d.c. unit costs may be derived by adding 0.05p/kwh to the a.c. unit costs. (This is an allowance for the additional maintenance which the d.c. conversion equipment would require.)

The sharp increase in unit cost with the drop in

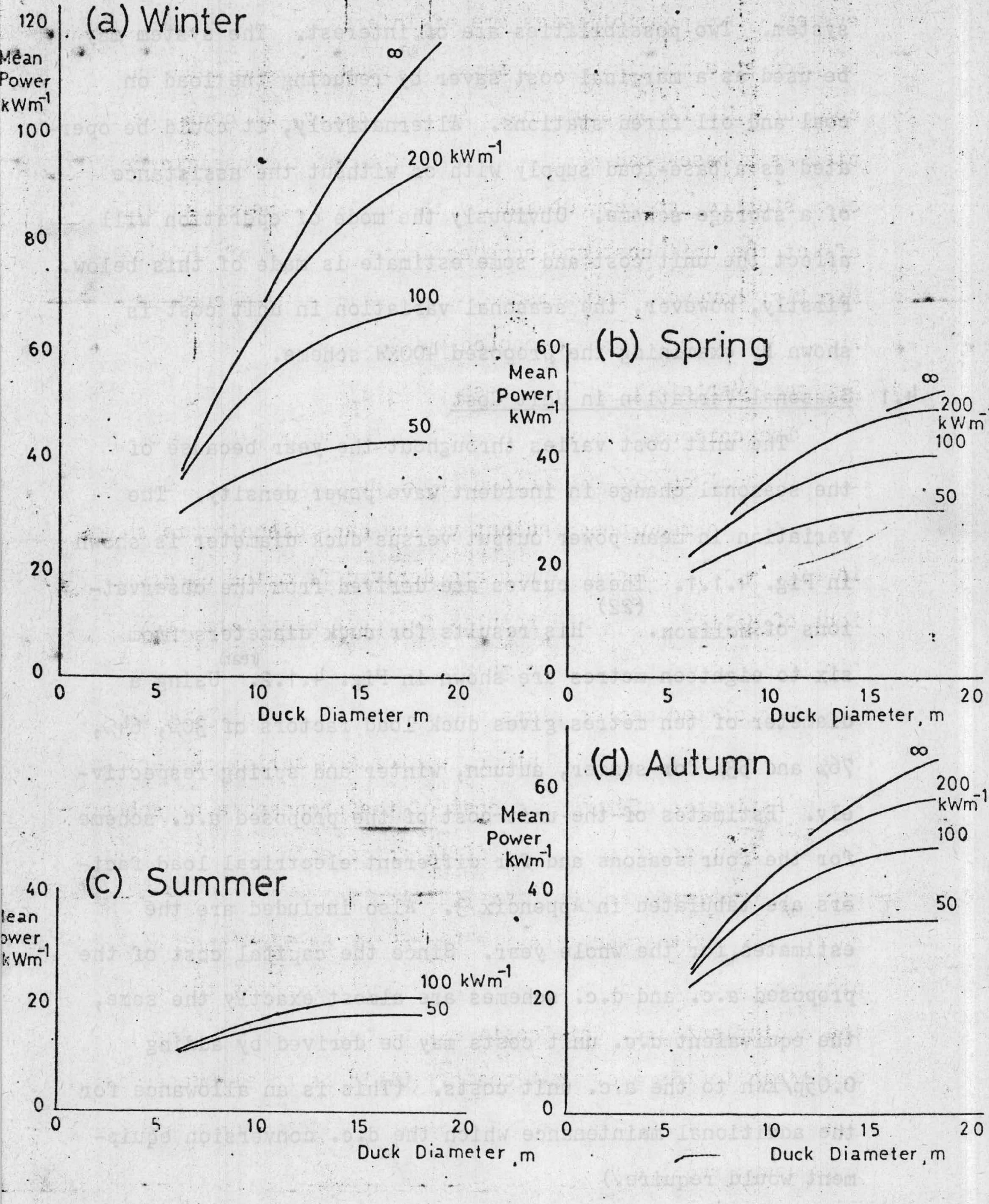


FIGURE 4.1.1 Seasonal Variation in Mean Power Output

FIGURE 4.1.3 Unit Cost (Summer)

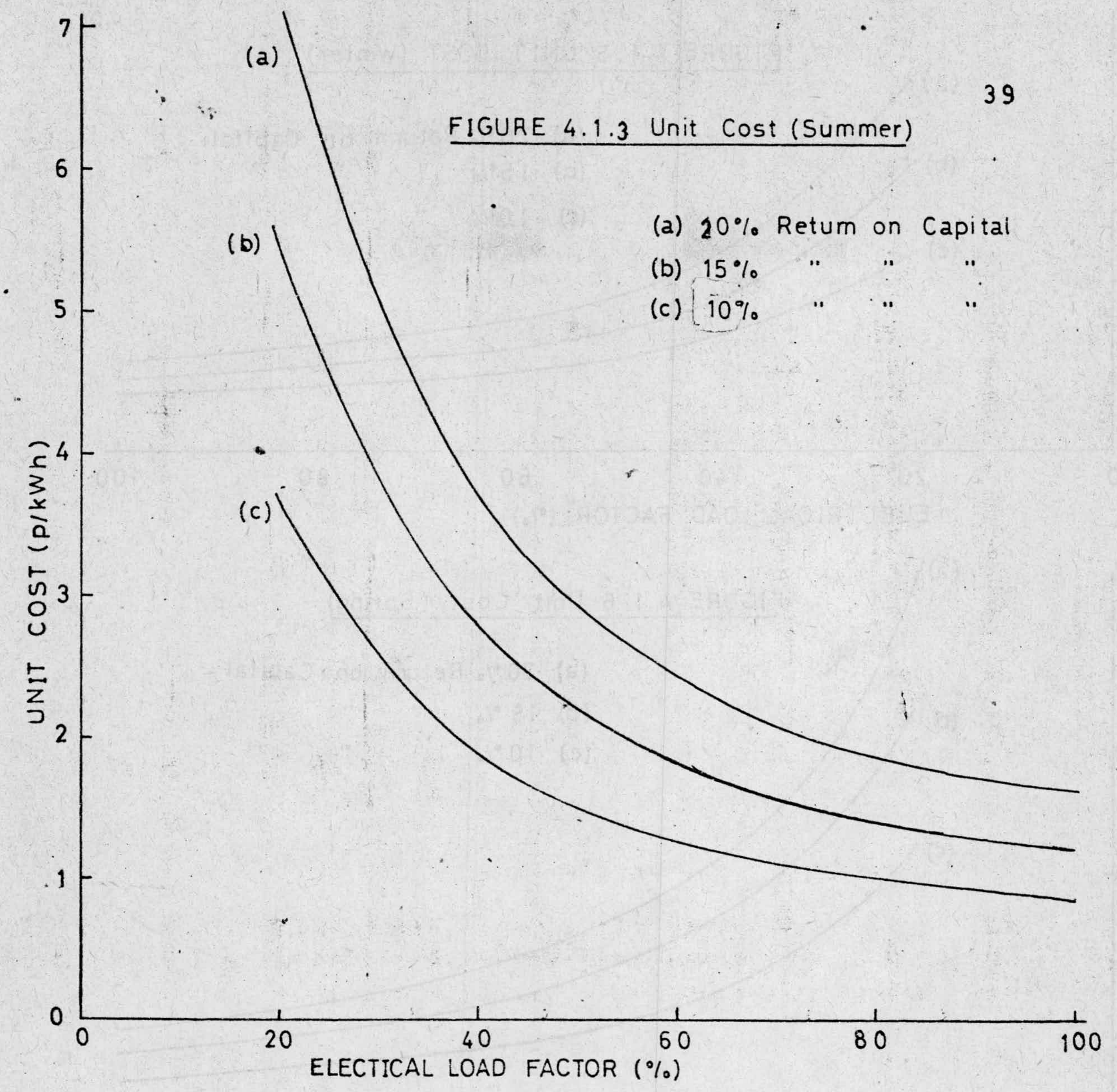
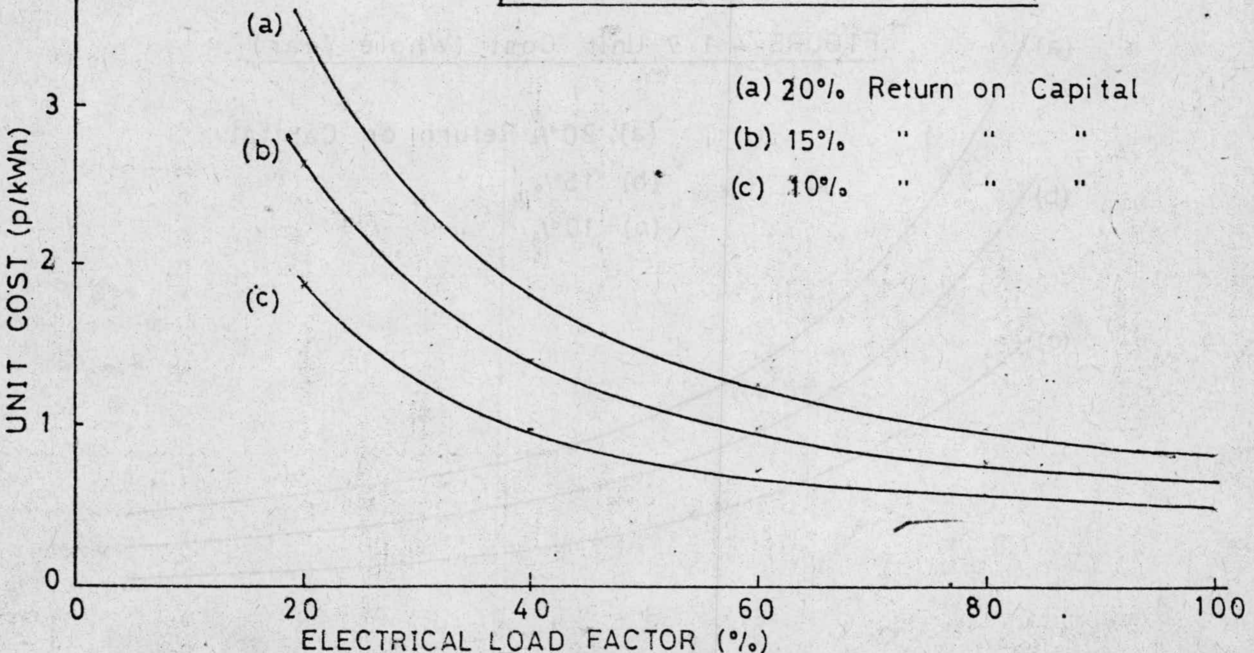


FIGURE 4.1.4 Unit Cost (Autumn)



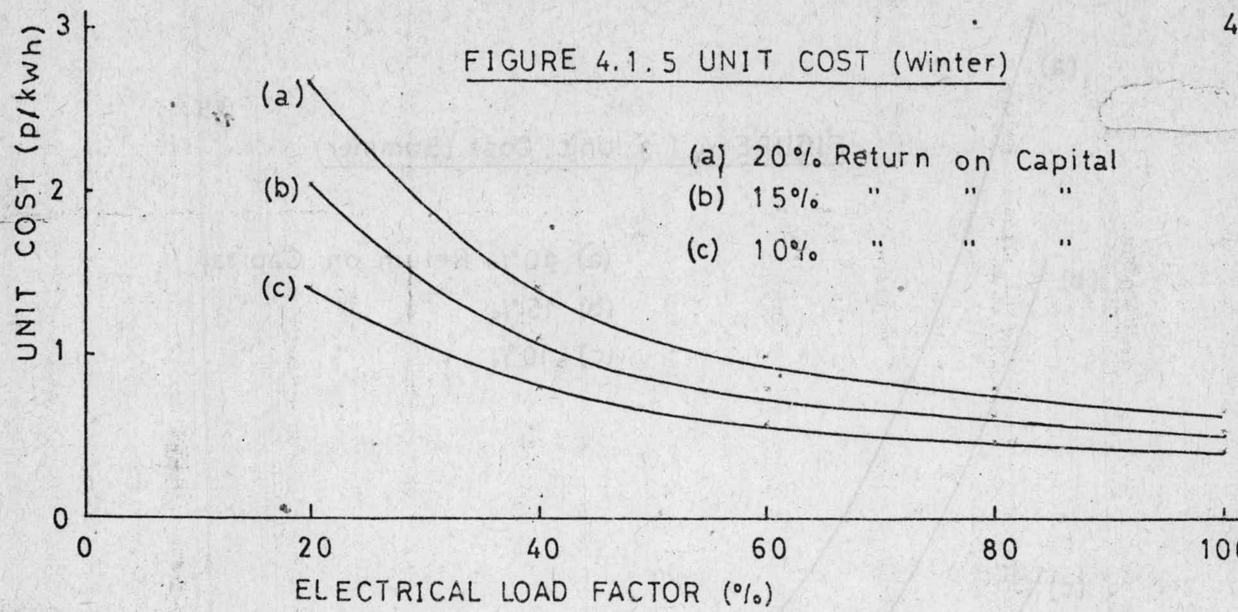


FIGURE 4.1.5 UNIT COST (Winter)

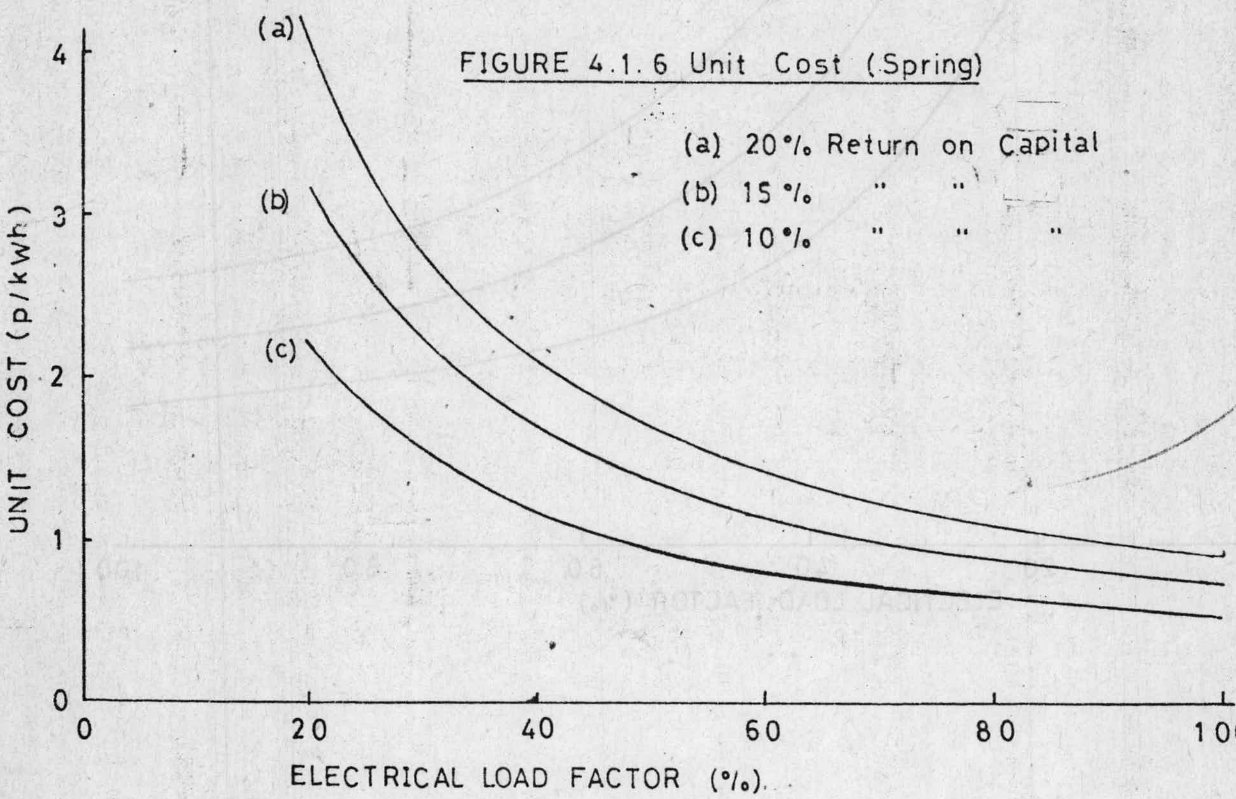


FIGURE 4.1.6 Unit Cost (Spring)

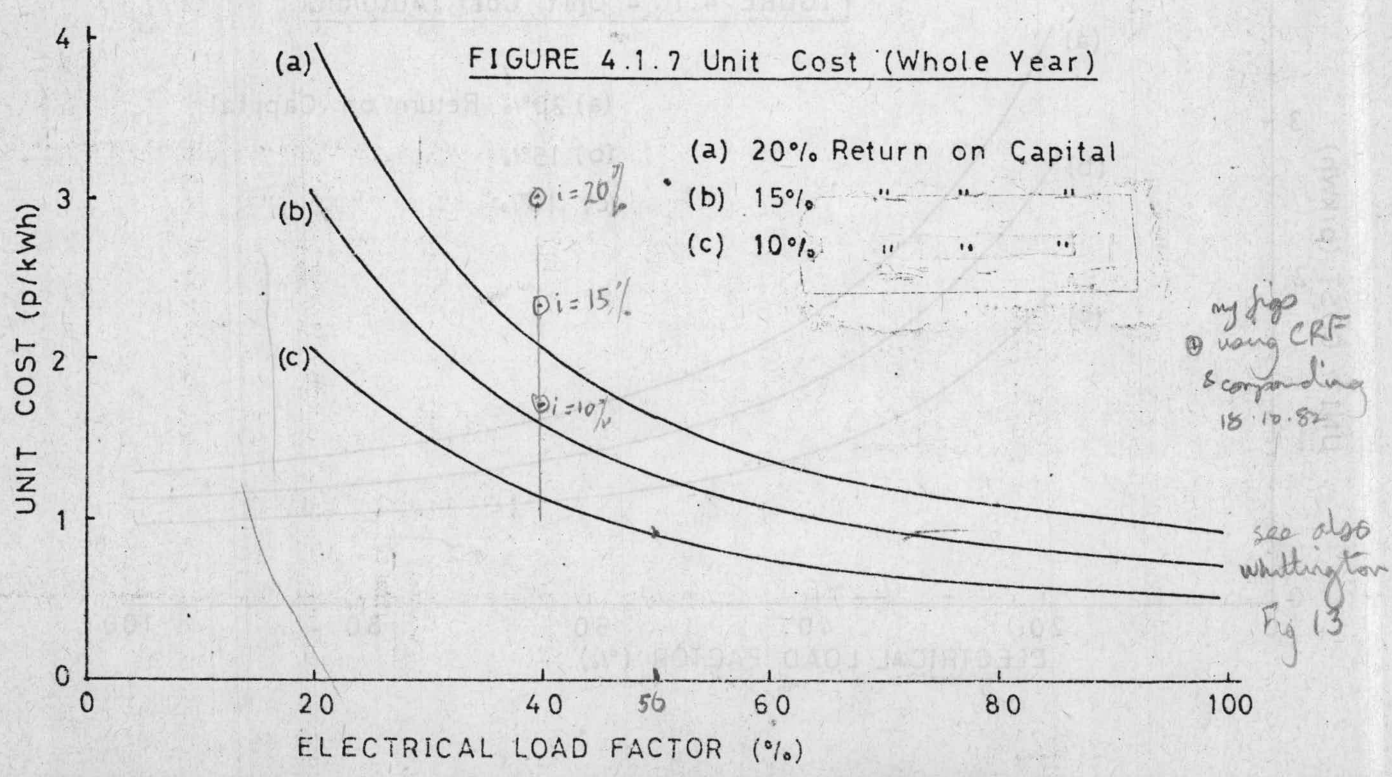


FIGURE 4.1.7 Unit Cost (Whole Year)

electrical load factor seen from Fig. 4.1.3 to Fig. 4.1.7. This situation is not peculiar to wave power and the curves are only intended to show the region of sharp increase in unit cost. In fact, the curves show that the electrical load factor would best be kept above 40%. As a basis for comparison of seasonal variations the unit cost for 40% electrical load factor is used. The repayment rate is difficult to ascertain and so the unit costs have been estimated at three different rates, (Appendix 3 : Tables). Again for ease of comparison the figures for a 15% rate of return are used.

As might be expected the poorest results are obtained in summer with unit costs reaching 2.8p/kWh. Winter, in the other extreme, costs 1p/kWh. The whole year output is 1.6p/kWh. It is difficult to acquire unit costs of nuclear and fossil fueled stations for direct comparison. The C.E.G.B. Statistical Yearbook 1974-75 gives some costs of generation. However, these appear not to include interest charges on capital loans and are made up from fuel costs, fuel handling costs and operation, repair and maintenance costs. The fuel costs for a wave power station are zero. Any unit costs of wave power based on operation, maintenance and repair would be order of magnitude estimates since there is, to date, no experience in the operation of wave power schemes. Indeed, the figure used for this in Appendix 3 is based on the total works cost of a nuclear station, including fuel and fuel handling.

What the figures do show is that, on an order of magnitude basis, it should cost pence, or fractions thereof, not pounds to deliver a unit of electricity from a wave power scheme.

4.2 Base Load Operation

At first sight wave power may appear unreliable and unsuitable for use as base load power. However, the time constants which operate in the North Atlantic are of days rather than hours and it should be possible to predict with reasonable accuracy the available power more than a week in advance. Moreover, it is unlikely that similar prevailing weather conditions will occur along the entire coast line of Great Britain. It is, therefore likely that if wave power schemes were to supply a significant percentage of the country's energy demand, these schemes would be distributed around the coast. Naturally, this would be done with due regard to shipping lanes, fishing grounds etc.

In base load operation, the electrical load factor is always as near 100% as possible. The problem is deciding the firm capacity of an installation. The supply would vary from day to day but would be predictable a week in advance. It will also follow a seasonal trend. However, from the results of Hoffman[22] for mean power output for a ten metre diameter duck (Fig. 3.1.1) the whole year load factor for a duck designed for $50kWm^{-1}$ seas will be about 56%. Allowing for losses in generation, transformation and transmission to shore, this will drop to about 50%. A 3000MW installation made up from four 800MW stations geographically distant from one another (e.g. one in the Western Approaches, one off the Outer Hebrides, one off the Shetlands and one off the Moray Firth) could reasonably be expected to produce 1500MW of firm capacity. Such an installation would cost about £520,000,000 giving a price per kilowatt of £350. (This is the price to bring the power only to the nearest landfall and considerable grid reinforcement would be necessary in some areas e.g. Outer Hebrides.)

4.3 Marginal Cost Saving

Marginal cost saving could be effected by off-loading coal and oil stations when wave power is available. At least two operational philosophies are possible:

(a) Because of the long time constants in the sea, it should be possible to predict how much power would be available from any wave power installations, say a week in advance. If sufficient power appears to be available conventional power stations of the equivalent predicted capacity could be shut down completely. The amount saved would therefore be the fuel cost of the closed down stations. This amounts to 0.64p/kWh on average. Other benefits of this system would be that the shut-down plant would be available for inspection and maintenance.

(b) The load in several conventional stations could be reduced by a small percentage (up to 10%). The small reductions would total the capacity of available wave power. The percentage reduction in load is kept small because of the sharp drop in efficiency of conventional power stations, when the output is reduced by more than 10%. The approximation is made that in the upper part of the thermal efficiency/output curve (i.e. 90-100% of output) there is a linear relationship between the power output and fuel used. Therefore, if there were a drop in the station output of 10% there would be a 10% saving in fuel costs. Marginal cost saving is made up from the fuel saved at each station.

Because of the assumed linear relationship, the marginal cost saving with this system is the same as for case (a).

However, thermal cycling of machines is an important factor in the determination of their life time. If maintenance is not required to be carried out on any machine then this system is best used to reduce thermal cycling. Also, there is all the reduced capacity running as spinning reserve in case of sudden peak demands.

4.4 Review of Unit Costs

The uniqueness of wave power means that it does not fall easily into any of the established categories of operation. A week is not really sufficient notice to consider wave power as true base load. Nor, since the fuel is free, does it seem practical to operate wave power stations at peak demand periods only. Pumped storage will not help to even out the output as this operates on a 24-hour cycle, and the wave power devices would require stand-by capacity to help boost output during perhaps a week of calm seas.

It seems appropriate to operate wave power devices at all times unless there is a point where low power levels cause more wear to the system than is thought reasonable. Case (b) of section 4.3 seems best in this respect. The wave power devices would work at 100% electrical load factor and the amount of power available would be known with reasonable accuracy. Warm spinning reserve is available if the anticipated power levels are not reached. The direct fuel savings could amount to £84,000,000 per annum from a 3000MW installed capacity scheme costing perhaps £700,000,000 (assuming fuel saving of 0.64p/kWh and a whole year average output of 1500MW).

5 Reliability

It is appropriate to start a discussion on reliability with some definitions. The reliability of a device is the probability that it will continue to operate for a desired period of time under the operating conditions met. Availability is the probability that a component or system is operating under certain conditions at a given instant in time. Component failure rate(λ) and repair rate(μ) determine the reliability and availability of a network. Also, mean time to failure (M.T.T.F.), mean time between failure (M.T.B.F.), and mean time to repair (M.T.T.R.) or mean outage time (including maintenance) are important self-explanatory parameters in the overall concept of reliability. Failure has different causes and degrees. A component may fail through misuse when stressed beyond its capabilities or it may fail because of wear caused by aging. Also, failure can arise from inherent weakness in the component when operating within its stated capabilities. Degrees of failure are partial or complete. An instance of partial failure in the considered scheme would be, say, a small hydraulic leak resulting in the loss of some pressure. Complete failure requires the shutdown of the component until repairs are effected. Redundancy which is often used in connection with reliability, arises when within a system or component there is more than one way of performing a given function or the system has the capacity to function, without failing, beyond the normal operating conditions imposed upon it. Active redundancy would involve the operation of components below their rated capacity. Standby redundancy is when an alternative component or means of performing a given function is always available but not in operation until required. It is as well to mention the proposed operational philosophy which the report assumes. Any minor faults occuring in the system would be isolated and left until the annual maintenance and repair work was carried out during the summer. The system would be designed to permit this philosophy to be extended to major components such as submarine links. However, attempts to repair major faults (it is anticipated that the weather would be the limiting factor here) would be made as soon as possible. No outages for maintenance would occur until the annual summer inspection when it would be hoped that the available redundancy would maintain output levels.

The starting point of a reliability analysis is the failure data of all the components which make up the system. The full analysis of any system containing redundant capacity requires computer modelling.(23) Although this has not been done here, a step-by-step approach has been used in an attempt to bring the question of reliability into perspective.

5.1 The Generators

No detailed data has been collected on the reliability, but a firm operation life of five years has been assumed,(27) of the hydraulic system. This is regarded as being part of the system which produces a torque-limited prime mover for electrical generation. However, it should be noted that much of the following discussion on generator redundancy, resulting from over-design capacity, applies equally to the hydraulic system.

Advances in generator design have improved their reliability considerably, although this statement is perhaps not accurate with regard to the largest (600MW) sets. However, it is true to say that the experience gained on large sets has led to more reliable small sets. The major advance in this field has been the advent of the brushless exciter design which is now preferred by most manufacturers.(24) The generators used would be of this type thereby eliminating the frequent inspection of slip rings or commutators.

The principle used to provide secure generation capacity in the proposed scheme is based on redundancy. Because of the possibility of damage to the generators by high incident wave power densities it was proposed to install twice the estimated required generation capacity. Theoretically, this means that up to 50% of the generators in each duck could fail without affecting average output levels. In practice, this may lead to stability problems and would render the remaining system susceptible to further damage from high seas. It is likely that with independent controllers on each generator stability problems could be overcome and torque limit adjustment could be made at the expense of some efficiency. A large 660MW brushless exciter machine has recently been designed to operate for twelve to eighteen months without shutdown.(25) Manufacturers of machines of appropriate size and design for the proposed scheme also considered their product to be capable of operating continuously for over twelve months.(15) It seems that electrical failure is very unlikely with reliability approaching that of transformers (once in every hundred years(26)). Any failure would almost certainly be of a mechanical nature and with only one moving part this has to be a main bearing fault. With such a small unit and regular maintenance it is unlikely that four generators in every eight will fail. With well-planned maintenance, generation capacity will almost certainly be maintained at 100%.

It is worthwhile to note that redundancy, as well as making mathematical modelling very difficult, may be used in several ways in the proposed scheme. If, through experience, bearing failure was found to cause most problems then four generators would be used as standby redundance. However, if electrical failures were found to occur then a policy of active redundancy would be employed, (eight generators working) thereby derating the machines. Almost any possible combination of machine states is possible (minimum of four fully-rated generators).

The a.c. controllers on the generators are estimated to be reliable for many thousands of operations.[16] This component life will span several years of real time. One of the possible operational policies would be to replace generators and possibly other components after five years of operation. Considering the state of the solid-state-component market, they may well become out-of-date in five years and would be replaced in any case.

Again, with 50% redundancy it is unlikely that a.c. controllers would have a major influence on security of generation. Their minimal cost means that they could be grossly overdesigned if difficulties were experienced.

5.2 Sea Bed Conversion

The reliability of this part of the system depends on the circuit configuration. Two schemes were mentioned in Chapter 2. The first of these involves four ducks feeding to a common busbar then to a 415V/11kV, 16MVA transformer which feeds to the sea bed. In this scheme the loss of the transformer or busbar would mean a drop in total output of 1.6% (one set of four ducks in a total of sixty-four). Transformer failure rates (λ) are variously quoted between $5 \times 10^{-6}h^{-1}$ [23] and $1.1 \times 10^{-6}h^{-1}$ [26]. Using equation 5.2.1,[23] for the reliability (successful operation) of the device for time t, this gives reliabilities between 95.7% and 99.0% respectively.

$$R(t) = e^{-\lambda t} \qquad (5.2.1)$$

Busbar failure rates are quoted as $1 \times 10^{-6}h^{-1}$ [23] giving 99% reliability. Now the reliability of two series components is much easier to analyse than that of parallel components and is given by equation 5.2.2.

$$R(t) = \exp\left(-\sum_i \lambda_i t\right) \qquad (5.2.2)$$

where i = 1, 2, ... the number of series components. Therefore the busbar and transformer in series give a reliability of 94.9%.

The flexible submarine links to the sea bed would have an average length of approximately 300m. Submarine cable faults occur on average once in ten years per twenty kilometres of cable, and take about 4½ weeks to repair.[26] This gives an approximate failure rate for each flexible link as $1.71 \times 10^{-7}h^{-1}$ and reliability of 99.9%. Regarding the busbar, on-board transformer and flexible cable as being a series link, the breaking of which would result in the loss of power from four ducks, gives an overall reliability of the link as 94.7%. The mean time between failure is given by $\frac{1}{\sum_i \lambda_i}$ [23] and for the above link this would work out at approximately twenty years. With sixty-four similar links in a 400MW scheme one could expect three failures per annum resulting in a maximum of 4.7% loss of whole year output.

With a feel for the reliability of the above system it is possible to anticipate how a system using one continuous (8km) busbar with transformers distributed at various points along its length would react,(Chapter 2). The number of transformers would be the same as above. However, these transformers, at 16 MVA, are 100% over-rated and half of them would be quite capable of taking full load. The busbar and flexible cable links are similarily over-rated. Therefore, it seems to be possible to improve the reliability of the busbar-transformer-sea bed link, to virtually 100% at no additional expense. (See technical problems associated with this scheme in Chapter 2.)

5.3 Sea Bed Processing

If the metal housing can be made to withstand the corrosive elements in its environment then the a.c. processing station would be reasonably reliable. With only one busbar, one transformer and one circuit breaker the total failure rate amounts to $16 \times 10^{-6} h^{-1}$. (Circuit breaker: $\lambda = 10 \times 10^{-6} h^{-1}$.) Reliability would be 87% (using equation 5.2.2) and the mean time between failures would be more than 7 years.

The d.c. processing station is less reliable. As can be seen from Figure 5.3.1. the percentage loss of availability due to d.c. plant failure in all high voltage d.c. systems throughout the world is very small.[27] However, Table 5.3.1 from the same reference shows that at least one fault occurs every year. It is not made clear whether the faults occur in the rectifier or the inverter. It is more likely that the faults were in the inverters where more complex thyristor bridges are used. (The rectifier would use a diode bridge.)

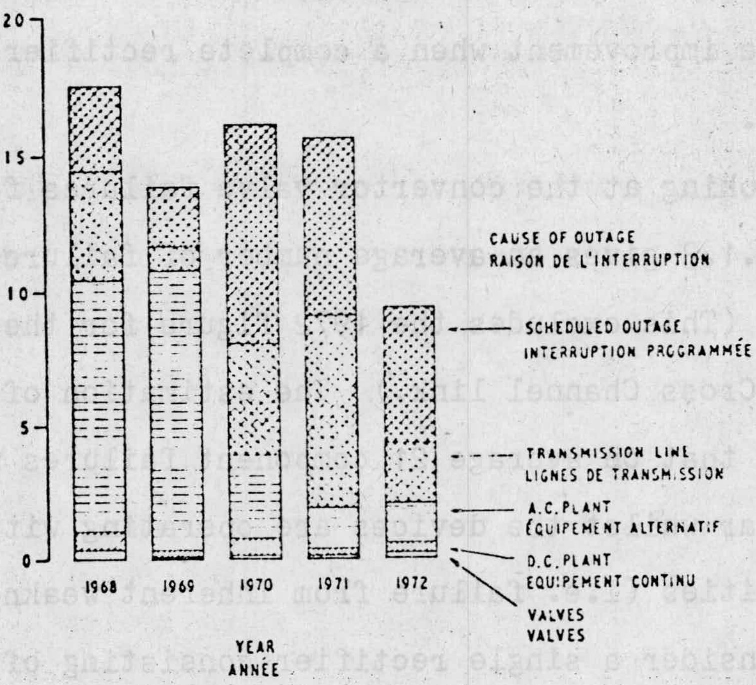


Figure 5.3.1 Average loss of equivalent availability of HVDC systems

For such an inaccessible site it is not the outage time which is important parameter but the number of faults which have a detremental effect on output levels until a repair is effected. Methods of reducing these include derating the electronic components; the use of high reliability parts involving special testing of individual components and the building in of redundancy. Of these the most effective would seem to be redundancy, perhaps on the same scale as the on-duck scheme. This has not been costed in previous chapters but at £2M for a rectifier it may not be excessive considering the possible improvement in reliability. An attempt is now made to assess this possible improvement when a complete rectifier is used as standby.

Looking at the convertor valve failures for 1972 from Table 5.1.3 gives an average number of failures per annum of 21. (This excludes the 1972 figure for the French station of the Cross Channel link.) The estimation of reliability assumes that on average 21 component failures will occur each year whilst the devices are operating within their design capabilities (i.e. failure from inherent weakness).

Consider a single rectifier consisting of 64 bridges (one for each power input cable). If there are no bypass switches then one component failure would put the whole bridge out of action. If there were bypass switches then a component failure would result in the loss of 1/64 of input power. On average there are 21 faults per annum and so the mean time between failures is 17 days. The fraction of full power output which could be reasonably expected is given by considering the area of the rectangle plus the area of the triangle in

Figure 5.3.2. This is:

$$\left(\frac{43}{64} \times 1\right) + \left(\frac{1}{2} \times \frac{348}{365} \times \frac{21}{64}\right)$$
$$= 0.83$$

In the worst case all 21 faults would occur in the first day and the total power output would be 43/64 of the total capacity (i.e. the rectangular area in Figure 5.3.2).

In chapter 4 it was estimated that £84M could be saved on conventional power station fuel bills by using wave power whenever it was available. If 0.17 of the available wave power was lost due to rectifier failure, then £14.3M would be the drop in coal and oil savings. In the worst case £28M would be the estimated drop in savings.

Now consider the double rectifier situation. One complete rectifier is used as standby redundancy and one of its bridges is switched in when a bridge in the first rectifier fails. In the worst case there would be twenty-one faults in the first day. These would destroy ten pairs of bridges and the system would operate at 54/64 of full power for a year. The loss in savings would be £13,000,000 - less than the average figures for the single rectifier case.

It is extremely difficult to work out the power lost in the double rectifier scheme when the twenty-one faults occur at regular intervals throughout the year. Figure 5.3.3 is used to help simplify and explain the problem. Constructed in a similar manner as Fig. 5.3.2 the lower rectangle represents the worst case power output for a year. However, the probable contour of the upper curve will not be a straight line joining the two end points. This is easily seen since after twenty-one faults there need not be any lines faulted. Indeed, it is unlikely that the twenty-one faults will occur on pairs of bridges. Therefore, by using a straight line

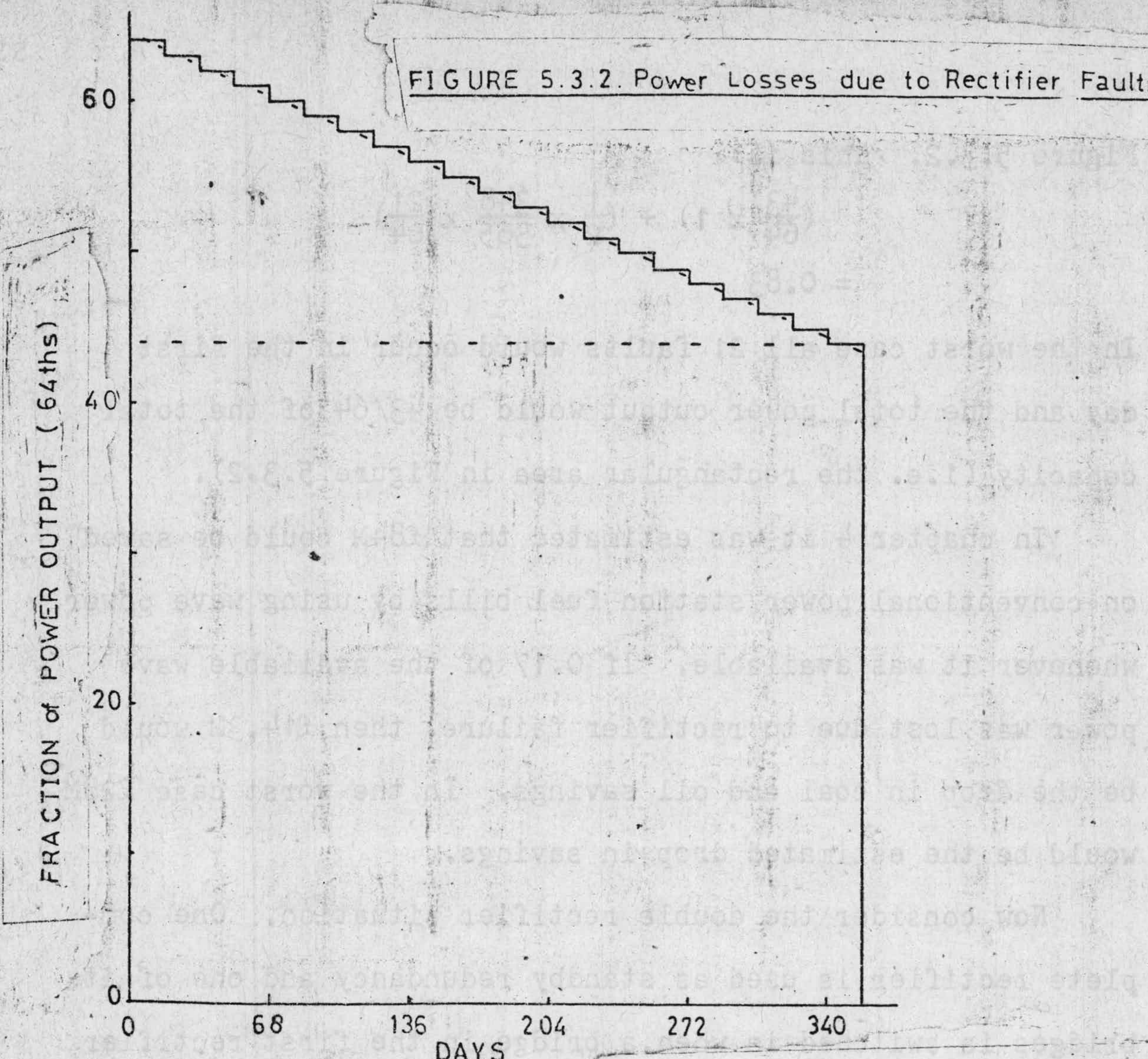


FIGURE 5.3.2. Power Losses due to Rectifier Faults

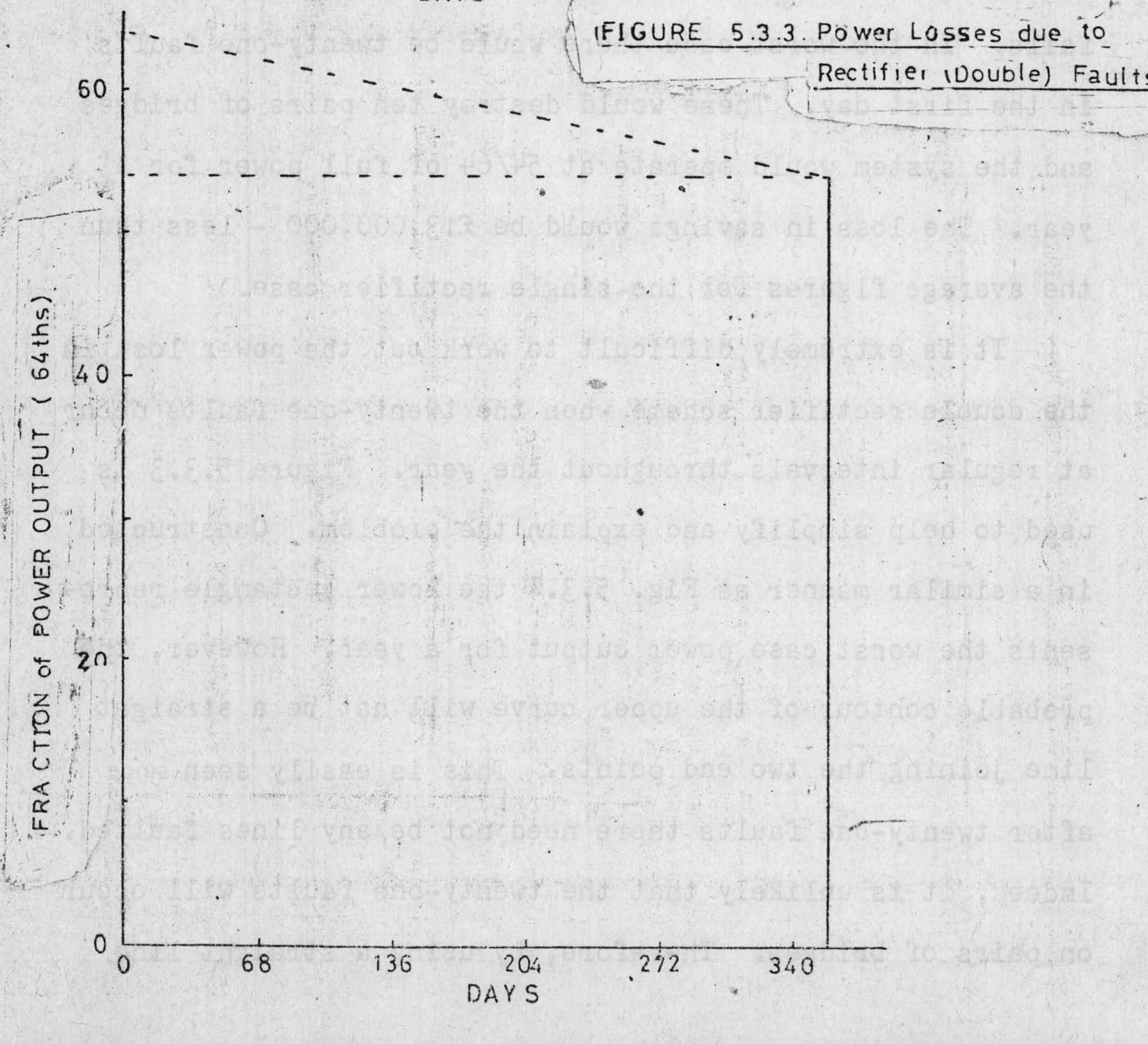


FIGURE 5.3.3. Power Losses due to Rectifier (Double) Faults

between end points as an approximation the results obtained will err on the conservative side.

The fraction of full power output which would reasonably be expected over a year is again given by considering the enclosed area.

$$= \left(\frac{54}{64} \times 1\right) + \left(\frac{1}{2} \times \frac{10}{64}\right)$$

$$= 0.92$$

This would result in lost savings of £6.7m.

A comparison of the loss in conventional fuel savings between the single and the double rectifier schemes shows an approximate improvement of at least £7M when a standby rectifier is incorporated. As quoted in Chapter 3 a standby rectifier would cost about £16M, i.e. £1.6M per annum at a capital return rate of 10%. On balance then the standby rectifier would seem to be worthwhile and is therefore included in the cost of scheme (c) in Appendix 3.

The probability of losing 1/64 of the power due to failures in a double rectifier scheme can be estimated. This is done by developing a series (Appendix 5). The probability of the double rectifier scheme working for a year without failure is taken from Table A5.2 as being 76%. This compares with 87% as the reliability of an a.c. scheme. It must be noted that a.c. failure would result in the loss of 400MW as opposed to 62.5MW in the d.c. case.

5.4 Transmission Ashore

As mentioned in section 5.2 cable faults occur once every ten years per twenty kilometres of cable. The proposed schemes would lie approximately twenty kilometres offshore and so one fault could be expected every ten years. This gives a reliability of 90.5%.

The failure of submarine cables tends to be due to external influences such as fishing activities or the dragging of ships' anchors. The greatest improvement in reliability would therefore be brought about by introducing redundancy in the form of an extra cable. This cable may be used as active redundancy to derate the existing cables, thereby reducing the probability of failure due to inherent cable weaknesses. In a 300 km link consisting of 9 cables, one a standby, (as proposed in Appendix 3) there would be approximately 14 faults per year, each taking 4½ weeks to repair.(26) This means that one repair ship could not cope with all the faults.

Overhead line faults occur on average three times per annum per 15km of line and take about 5 hours to repair.(26) The over-land schemes propose 370km of line and so there would be approximately 75 faults per annum. Each of the proposed 765kV circuits would therefore be down for 190 hours per year.

Convertor reliability is taken as being the same as for the single rectifier scheme discussed earlier. That is 21 faults per year on average, each taking about 3 hours to repair (from Table 5.3.1).

5.5 Review of Reliability

This brief discussion of reliability has reavealed several important points:

(a) As far as the electrical generation, transformation and feeding to the sea bed are concerned, there is sufficient redundancy to ensure reliable performance without standby barrages. The reliability of the civil installation may, however, warrant the inclusion of a spare. The cost and details of a system designed with the benifit of all the information gathered in this report is detailed and costed in Appendix 3.

(b) The real problems with reliability arise down stream of the flexible cable links. An a.c. processing station would fail approximately once every 7 years and may also require a shut down of 400MW of power every year for maintenance. Including the maintenance of circuit breakers and auxiliary equipment this would come to about 4 days a year.[26]

(c) The d.c. processing station with two rectifiers, one as standby, is sufficiently reliable if all damaged bridges are replaced once every year. This would also require shut down of 400MW of capacity for several days.

(d) The submarine links of 20km can be made reliable by laying sufficient extra cables as redundancy. As well as their extra cost per metre length of link, some additional switching and cabling arrangements would have to be made between the sea bed stations in order that the redundant cables may be used to carry the power from any of the processing stations in a large scheme.

(e) Because of the reliability considerations, a 300km submarine link at 250kV d.c. does not appear to be feasible. At 400kV d.c. a 3000MW scheme would require only six instead of the original nine cables, but on average, 40 weeks per year would be required to repair the nine faults which would occur. This is still not really practical.

(f) Unless the convertor were also to have a significant amount of redundancy the station would require manning (or at least be fairly readily accessible).

6. Conclusions and Recommendations

This report has attempted to assess the economic feasibility and reliability of large scale electrical generation from wave power by studying a small 400MW modular unit. The principal results of the study are that:

(a) a.c. and d.c. generation and transmission over twenty kilometres of submarine link to the nearest landfall would cost approximately the same.

(b) the cost per kilowatt from a large scheme, at less than £300, would be competitive with nuclear power. (for power delivered by four hundred kilometres of submarine cable and overhead line to the load centre)

(c) the unit cost of electricity from a wave power scheme will be of the order of pence, including capital repayment charges.

(d) a 3000MW scheme could save over £80,000,000 per year in coal and oil fuel costs.

(e) the reliability of the electrical system could be made adequate by the inclusion of sufficient redundancy. The scheme would appear to remain economic even with this redundancy.

At the present stage of wave power development ideas are still diverging. This report must therefore recommend further research into all the possible options with a view to gathering sufficient information from which one or perhaps two schemes emerge as being the most promising.

The report recommends :

(a) further work into the best operational mode and the conventional fuel savings to be made.

(b) there are obvious possibilities for a long overhead d.c. link which require investigation.

(c) because of the stability problems of coupling a.c. systems and the little differences in cost between a.c. and d.c. generation, transmission ashore should be by d.c.

(d) computer modelling of promising schemes to determine more precisely the optimum amount of redundancy to be included.

(e) an economic evaluation of "jetting"(entrenching submarine cables in the sea bed) to increase reliability and reduce repair costs resulting from external influences and abrasion.

(f) a study of accessibility for maintenance and repair purposes.

(g) a study of the requirements for standby capacity in the case of calm seas.

(h) a study to find the optimum number of generators and the optimum combination of standby redundancy and active redundancy.

It must be said that when in doubt costs have been overestimated, and also that in all schemes the redundancy included was an overestimate since in most cases this amounted to 100%. Nevertheless, within the wide limits of accuracy the results of the study were strongly indicative that electrical generation from wave power could be economically feasible.

The final decision may, however, not lie in the hands of the economist nor the design engineer, but in the hands of the politician and it is perhaps ironic that the future of a clean and non-polluting source of energy may be condemned by environmentalists.

Acknowledgements

I would like to express my gratitude to Dr. H.W. Whittington for his guidance, to Miss K. Milne for her careful typing of the manuscript and to Miss G. Milne for her support during the course of this study.

Appendix 1

Capital Cost of A.C. Scheme

The calculation is based on the proposed generating system of sixty-four four-duck units feeding to the sea bed. Transmission costs are based on twenty kilometres of submarine cable which would be the required length to carry the power to the nearest land fall. This measure is taken since it seems likely from power loss considerations that the voltage would be stepped-up to perhaps 765kV for overland transmission from a remote site such as the Outer Hebrides.[8] It is also a reasonable length of submarine cable for use in other sites e.g. the Moray Firth.

CIVIL INSTALLATION

Capacity	400MVA
Duck diameter	10m
Incident wave power density	$50kWm^{-1}$
Length of installation	8000m
Cost of duck construction	$£500m^{-1}$ diameter, m^{-1} length
Total duck cost	£40,000,000

Continued overleaf / Electrical Installation

ELECTRICAL INSTALLATION

	£M
Generators	5.4
Motors	6.0
A.C. controllers	0.8
Flexible busbar	0.2
On-Board transformers	1.7
Flexible cable	0.1
Sea bed housing	0.1
Sea bed transformer	0.8
Circuit breaker and protection	0.4
Submarine cable (20km)	10.0
Laying cost (20km)	0.2
Total	£25.7

There are power losses in the scheme which must be costed and included in the total capital cost. The costs of losses per kilowatt are taken from reference 10.

LOSSES

A.C. Cable Specification

Line voltage	275kV
Current carrying capacity per conductor	800A
Conductor cross-sectional area	$500mm^2$
Resistance per conductor	$0.04 ohm\ km^{-1}$
Charging current	$5A\ km^{-1}$

For a twenty kilometre run, assuming single cable, the charging current per conductor = 100A.

Assuming generation efficiency of 0.96

and transformation efficiency of 0.98 :-

MVA available for transmission	$= \text{Generator power} \times \eta_g \times \eta_t$
	$= 400 \times 0.96 \times 0.98$
	$= \underline{\underline{376\text{MVA}}}$
Current per conductor	$= \dfrac{P \times 3}{3 \times V_{line}}$
	$= \dfrac{376 \times 10^6}{3 \times 275 \times 10^3}$
	$= \underline{\underline{790\text{A}}}$
Power into cable at full load	$= 3\, V_{line}\, I_{line} \cos\theta$
	$= 3 \times 275 \times 10^3 (790^2 - 100^2)^{\frac{1}{2}}$
	$= \underline{\underline{373\text{MW}}}$
Loss per conductor	$= I^2R$
	$= 790^2 \times 0.043 \times 20$
	$= \underline{\underline{0.54\text{MW}}}$
Total cable loss	1.6MW
∴ Transmitted power	$= 373 - 1.6$
	$\underline{\underline{371\text{MW}}}$

Assuming transformation efficiency of 0.98 at the receiving end :

Full-load power	$= 364\text{MW}$
∴ Losses	$= \underline{\underline{36\text{MW}}}$

Cost of a.c. losses(10)	£ per kW
Generating equipment	20.00
Transformers	10.00
Terminal equipment	12.00
Cable	20.00
	£62.00

Cost of losses	$= 62 \times 36 \times 10^3$
	$= \underline{\underline{£2.2\text{M}}}$

TOTAL CAPITAL COST

	£M
Civil	40.00
Electrical system	25.70
Losses	2.20
Total capital cost	£68.00

Cost per kilowatt delivered to land £190.00

$\pounds 68 \times 10^6$
$\frac{364}{\cancel{4\times} 10^5}$

17

Appendix 2

Capital Cost of D.C. Scheme

As with the a.c. scheme this estimation is based on the use of twenty kilometres of submarine cable to carry the power to the nearest landfall.

CIVIL INSTALLATION

As for a.c. scheme, Appendix 1.

Total duck cost = £40,000,000

ELECTRICAL INSTALLATION

	£M
Generators	5.4
Motors	6.0
A.C. controllers	0.8
Flexible busbar	0.2
On-Board transformer	1.7
Flexible cable	0.1
Sea bed housing	0.1
Rectifier	2.0
Submarine cable (20km)	4.0
Laying cost (20km)	0.2
Total	£20.5

Unlike the a.c. case there are no charging current losses, only I^2R losses.

Continued overleaf/Losses

LOSSES

D.C. Cable Specification

Cable voltage	$\pm$250KV
Number of conductors	2
Current carrying capacity per conductor	800A
Cross sectional area of conductor	500mm^2
Resistance per conductor	0.043ohm km^{-1}

Assuming generation efficiency of 0.96
and transformation efficiency of 0.98
and conversion efficiency of 0.95

Power into cable $= \text{Generator power} \times \eta_g \times \eta_t \times \eta_c$

$= 400 \times 0.96 \times 0.98 \times 0.95$

$= \underline{358\text{MW}}$

Current in cable $= P/V$

$= \dfrac{358 \times 10^6}{250 \times 10^6} \times \frac{1}{2}$

$= \underline{716\text{A}}$

Loss in cable $= I^2R$

$= 715^2 \times 0.043 \times 2 \times 20$

$= \underline{0.87\text{MW}}$

Power at the receiving end $= (\text{Power in} - \text{loss}) \times \eta_c$

$= (358 - 0.87) \times 0.95$

$= \underline{340\text{MW}}$

Total losses $= 400 - 340$

$= \underline{60\text{MW}}$

Cost of d.c. losses	£ per kW
Generating equipment	20.00
Transformers	10.00
Terminal equipment	35.00
Cable (20km)	5.00
	£70.00

Cost of losses $= 70 \times 60 \times 10^3$

$= \underline{£4.2\text{M}}$

TOTAL CAPITAL COST

	£M
Civil	40.00
Electrical	20.50
Losses	4.20
Total capital cost	£65.00
Cost per kilowatt delivered to land	£190.00

Appendix 3

Some Possible Large Scale Schemes (3000MW)

The figures used are mostly simple multiples of those tabulated in Chapter 3 since it is most likely that large scale schemes will be made from modular units.

A unit size of 400MW (described in Chapter 2) is used here. (N.B. from Appendices 1 and 2 cost per kilowatt to nearest landfall is £190).

(A) From Outer Hebrides 275kV overland to Glasgow.

	a.c.	d.c.
	£M	£M
Eight 400MW barrages	418	418
Eight sea bed processing stations	10	17
Eight lengths of 40km submarine cable (to shore and between islands)	160	64
Eight lengths of 370km O/H line	184	72
Eight convertors and electrodes	-	68
	£772	£639
Cost per kilowatt (assuming 20% losses)	£320	£270

This scheme is very unreliable as it does not have spare submarine links which are necessary to aviod losing 12% of output every time there is a cable failure. If nine cables were laid then they could all be used to help transfer high output levels in seas of more than $50kWm^{-1}$.

Continued overleaf / (B)

(B) D.C. Submarine link to Argyll then overhead to Glasgow (250kV)

	£M
Eight 400MW barrages	418
Nine sea bed processing stations	17
Nine lengths of 300km submarine cable	540
Eight lengths of 100km O/H line	20
Eight convertors and electrodes	68
	£1063
Cost per kilowatt (assuming 30% losses)	£530

(C) 765kV overland

The work of Dinwiddie suggests that 765kV a.c. would be the best voltage for transmission. From the combined results of economic, technical and reliability studies by Dinwiddie and Roberts the following scheme seems to be the most promising to date.

	£M
Eight 400MW barrages	418
Eight sea bed processing stations (d.c.)	33
Nine d.c. links to Outer Hebrides (20km)	36
3000MW d.c. link across Uist (8km)(4p $kw^{-1} km^{-1}$)(28)	1
Nine d.c. links to Skye (25km)	45
Eight convertors and electrodes	68
Step-up transformer (275kV/765kV) (a.c.)	10
Overhead 765kV(28) (370km) (a.c.)	56
Step-down transformer (765kV/275kV)	10
	£677
Cost per kilowatt (assuming 20% losses)	£280

Appendix 4

Unit Cost of A.C. Scheme

Total capital cost of scheme = £68,000,000

Therefore annual cost at repayment rates of 10%, 15% and 20% is £6.8M, £10.2M and £13.6M respectively.

The computation used two formulae :

Number of units produced per annum = hours in a year x power delivered ashore x load factor of duck x electrical load factor (A4.1)

Annual cost = capital cost x rate of repayment (A4.2)

$$\therefore \text{Unit cost} = \frac{(A4.2)}{(A4.1)} + 0.15 \quad \text{p/kWh}$$

0.15p/kWh is allowed for the maintenance costs.

Summer

Electrical Load Factor	Repayment Rate (p/kWh)		
	10%	15%	20%
100%	0.86	1.22	1.57
80%	1.04	1.48	1.93
60%	1.33	1.93	2.52
40%	1.93	2.82	3.70
20%	3.70	5.48	7.26

Autumn

Electrical Load Factor	Repayment Rate (p/kWh)		
	10%	15%	20%
100%	0.48	0.65	0.82
80%	0.57	0.77	0.98
60%	0.71	0.98	1.26
40%	0.98	1.40	1.82
20%	1.87	2.65	3.48

Winter

Electrical Load Factor	Repayment Rate (p/kWh)		
	10%	15%	20%
100%	0.40	0.53	0.65
80%	0.46	0.62	0.78
60%	0.57	0.78	0.99
40%	0.78	1.09	1.41
20%	1.41	2.04	2.67

Spring

Electrical Load Factor	Repayment Rate (p/kWh)		
	10%	15%	20%
100%	0.55	0.75	0.95
80%	0.65	0.90	1.16
60%	0.82	1.16	1.49
40%	1.16	1.66	2.16
20%	2.16	3.17	4.17

Whole Year

Electrical Load Factor	Repayment Rate (p/kWh)		
10%	10%	15%	20%
100%	0.53	0.72	0.91
80%	0.63	0.86	1.10
60%	0.78	1.10	1.42
40%	1.10	1.58	2.05
20%	2.05	3.01	3.96

Appendix 5

Reliability of Double Rectifier

The double rectifier scheme is shown in Figure A5.1 (the three phase supplies to corresponding bridges being common). It should be emphasised that this scheme is considered merely for illustrative purposes. The eventual system may be considerably different in rating and design. The bank of three phase diode bridges on the left is used initially. When a bridge on the left fails and is disconnected the corresponding bridge on the right is switched on using its a.c. controller. Assuming a total of 21 faults per year, each of which causes a complete bridge failure, the probability of the complete rectifier remaining intact (i.e. capable of delivering full power) can be estimated.

The probability of losing power is the probability of failure of two corresponding bridges, e.g. 2a and 2b. After one fault the probability is zero since, say, bridge 2b is not used until bridge 2a has failed. Therefore:

P (intact after one fault) = 1

P (loss of power after two faults)

= P (two corresponding bridges in each rectifier failing, e.g. 2a & 2b)

$= 1/64 \times 1/64$

$= (1/64)^2$

$= P_2(L)$

P (intact after two faults = $1 - P_2(L)$

P (loss of power after three faults)

= P (intact after two faults) x P (fault will be on a bridge in the right-hand rectifier corresponding to a failed bridge in the left-hand rectifier.)

$= \left[1 - P_2(L)\right] \times 2/64$: since there will now be two faulted bridges in the left-hand side

$= P_3(L)$

P (intact after two faults) = $1 - P_3(L)$

The series is developed in Tables A5.1 and A5.2.

Note that when two corresponding bridges fail the by-pass switch is closed.

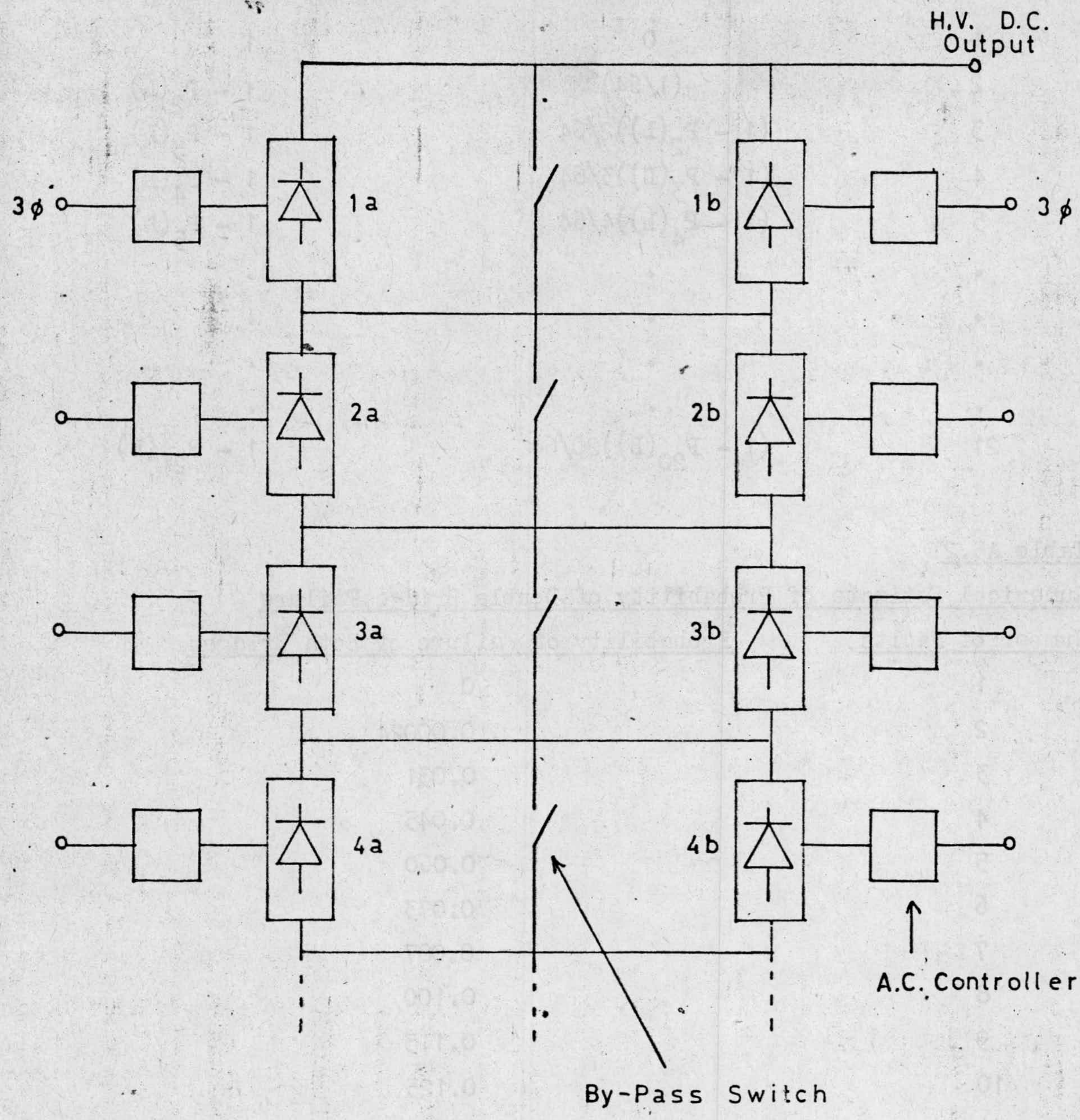


Figure A5.1 Double Rectifier

Table A5.1

Probability of Double Bridge Failure

Number of Faults	Probability of Failure of Both Bridges	Probability of Rectifier Remaining Intact, $P_n(L)$
1	0	1
2	$(1/64)^2$	$1 - P_2(L)$
3	$(1 - P_2(L))2/64$	$1 - P_3(L)$
4	$(1 - P_3(L))3/64$	$1 - P_4(L)$
5	$(1 - P_4(L))4/64$	$1 - P_5(L)$
.	.	.
.	.	.
.	.	.
.	.	.
21	$(1 - P_{20}(L))20/64$	$1 - P_{21}(L)$

Table A5.2

Numerical Estimate of Probability of Double Bridge Failure

Number of Faults	Probability of Failure of Both Bridges
1	0
2	0.00024
3	0.031
4	0.045
5	0.060
6	0.073
7	0.087
8	0.100
9	0.113
10	0.125
11	0.138
12	0.148
13	0.160
14	0.171
15	0.181
16	0.192
17	0.202
18	0.212
19	0.222
20	0.231
21	0.240

Table 1.1 World Coal Resources

x10^9 Tons

Region	Identified resources	Hypothetical resources	Estimated total
Asia & European U.S.S.R.	6300	3600	9900
Total U.S.S.R.	5900	2700	8600
North America	1600	2600	4200
Europe	560	190	750
Africa	72	140	212
Oceania	54	63	117
Central & South America	18	9	27
Total Coal Resources	8600	6600	15200

Source : Reference (1).

Table 1.2 World Uranium Reserves (thousands of tonnes)

Recovery cost \$/Kg of U_3O_8	10-20	20-30	30-60
Proven Resources	650	700	400
Possible Additional Resources	700	500	1100
Totals	1350	1200	1500

Table 3.1.1

Costs On-Board the Barrage

	£M
Civil cost	40.0
Motors	6.0
Generators	5.4
A.C. Convertors	0.8
Busbar	0.2
Transformers	1.7
Flexible cable	0.1
	£52.3

Table 3.2.1

Submarine Station Cost

	a.c.	d.c.
	£M	£M
Metal Housing	0.1	0.1
Transformer	0.8	-
Circuit Breaker and Protection	0.4	-
Rectifier	-	2.0
	£1.3	£2.1

Table 3.3.1

Transmission Costs

	a.c.	d.c.
	£'000	£'000
Submarine cable	500 km^{-1}	200 km^{-1}
Laying costs	8 km^{-1}	8 km^{-1}
Overhead line	61 km^{-1}	25 km^{-1}
Sea and earth electrode	500	500
Convertor	---	8000

Table 5.3.1

Number of Faults of >1 Minute and Equivalent Availability Lost 1971/1972

System or Station Upper Line - 1971 Lower Line - 1972		A.C. Filters and Sync. Compen-tor		Other A.C. Equipment		Convertor Valves		D.C. Equipment		Trans-mission Line		Tele-comm.		Human Error and Cause Unknown		Mainte-nance Outage h	Total Number of Events	Total Outage h
		No.	h:min	No.	h:min	No.	h:min	No.	h:min	No.	h:min	No.	h:min	No.	h:min			
Gotland		1	0:10	15	3:54	3	2:15	12	2:14	2	106			2	0:15	285	35 N A	400 600
Cross Chanel	GB	4 2	99:26 17:56	2	4:48	6 4	9:25 0:34	15 71	25:24 49:54	1	929	2 2	6:35 8:02			246 248	30 79	1 321 324
	F			1 9	947 11:27	29 460	5:51 43:20	1 19	1 92:40	 2	 51:25					920 63	31 490	1 874 1 437
Volgograd-Donbass				 8	 2:52	5 20	0:45 0:20	17 31	3:18 26:04	6 1	37:29 10:48			15 26	5:30 3:18	1 023 537	43 86	1 070 550
Konti-Skan	DK	1	4:14	1	0:19	4 4	0:12 0:52	6 8	5:26 1:35					2	1:24	312 279	14 12	324 282
	S			2 1	0:27 2:00	13 6	4:41 1:03	1 2	2:11 0:05	5 4	2 734 824			1 2	0:07 2:09	188 225	22 15	2 930 1 054
Sakuma 1						 1	 0:05									 686	N/A 1	N/A 686
New Zealand				 4	 3:49	 60	 5:21	 7	 0:56	 4	 4:22			 2	 0:02	 666	N/A 77	N A 681
Sardinia		3 5	17:39 7:58	5 4	4:57 7:17	23 55	5:34 17:12	30 43	120 139	35 35	1 163 912	1	0:05			646 653	97 142	1 958 1 737
Vancouver		 2	 8:33	4 9	5.05 15:33	23 27	12:30 28:35	15 3	38:44 14:05	 1	 1:04			14 6	3:36 0:19	1 027 541	56 48	1 087 609
Pacific Intertie	Cel.			3	13:30	15	2:33	10	8:19	1	0:06					282	29	O/S 305

N/A – Data not available

O/S – Out of Service

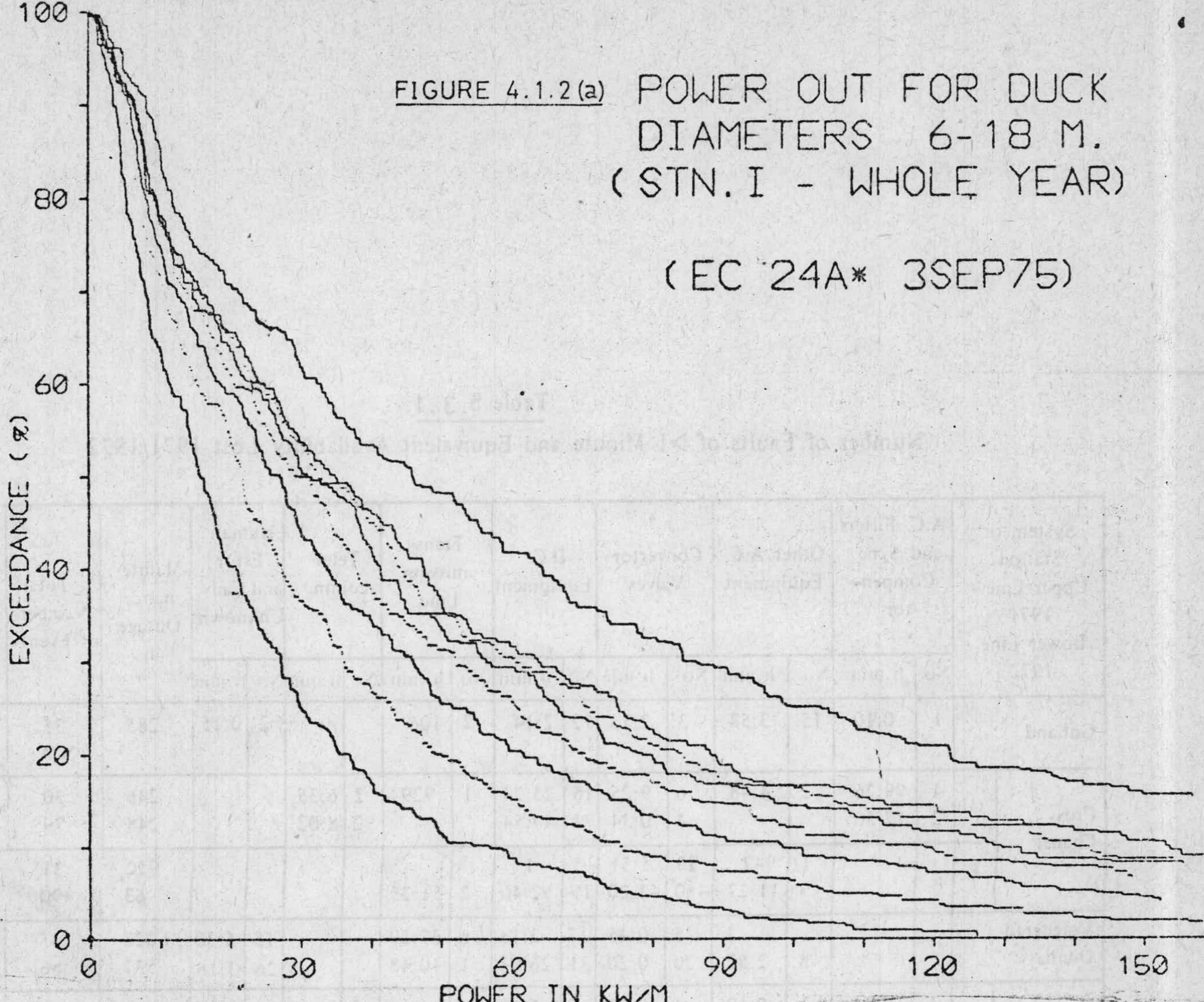


FIGURE 4.1.2(a) POWER OUT FOR DUCK DIAMETERS 6-18 M. (STN. I - WHOLE YEAR)

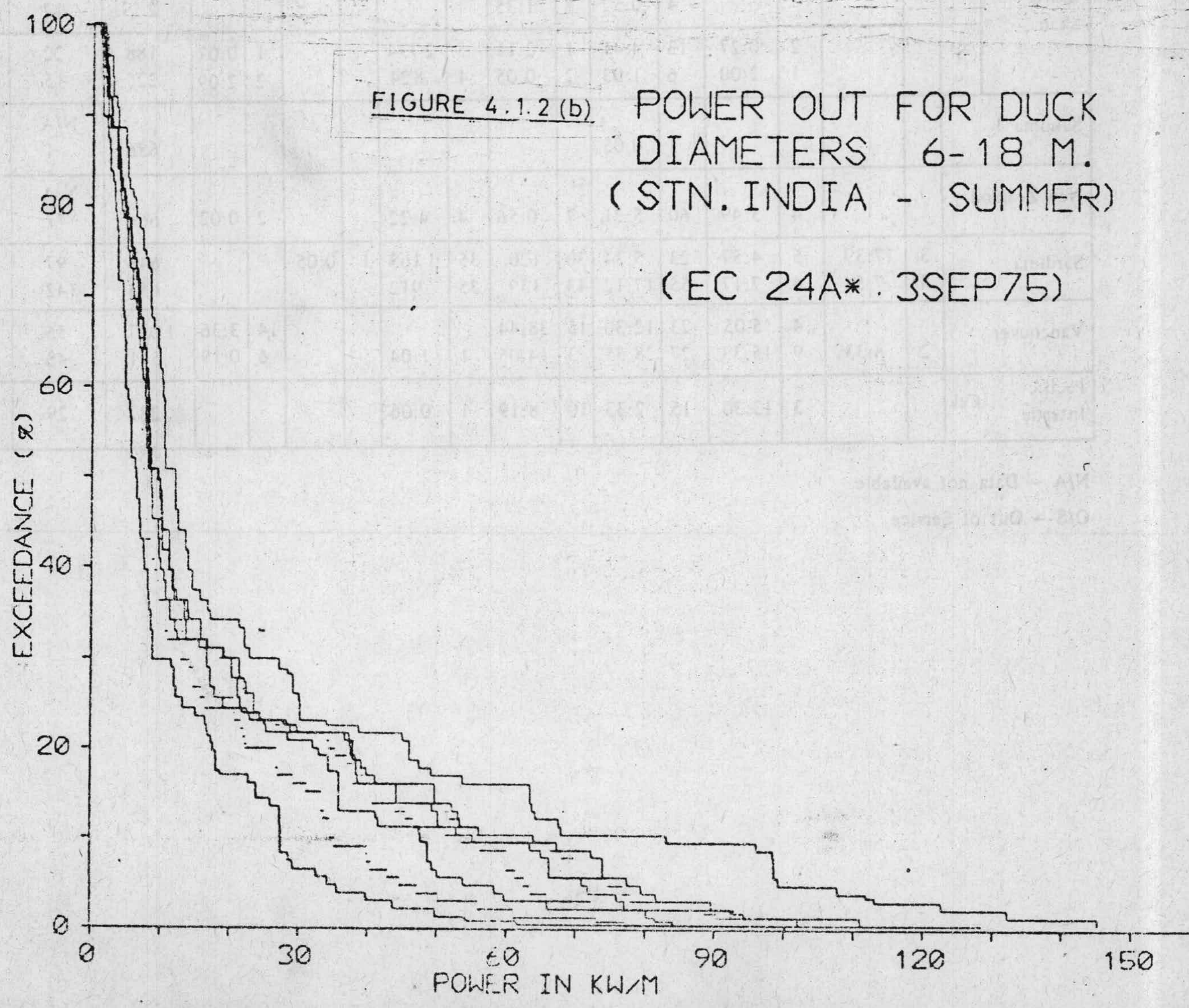


FIGURE 4.1.2(b) POWER OUT FOR DUCK DIAMETERS 6-18 M. (STN. INDIA - SUMMER)

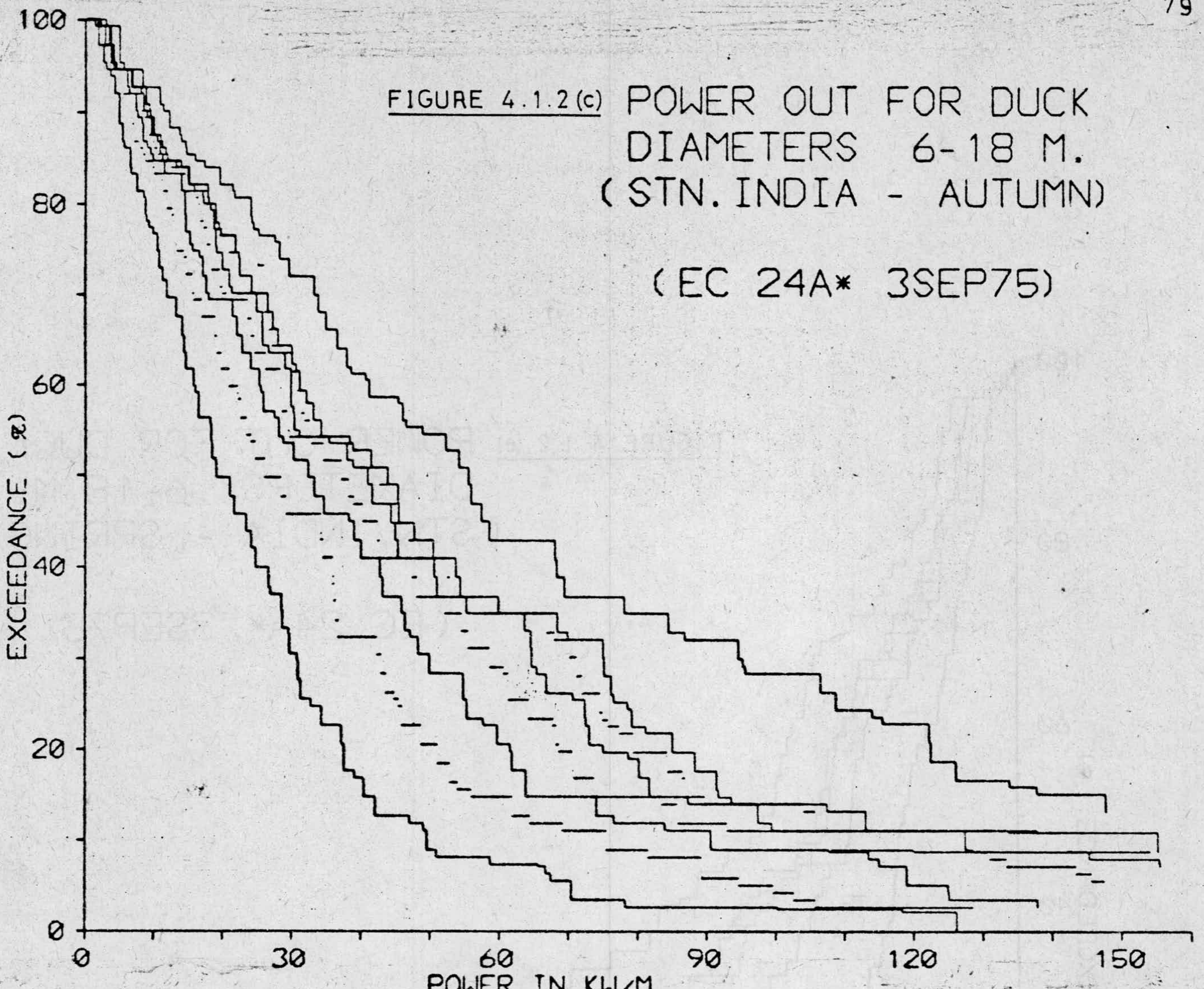


FIGURE 4.1.2(c) POWER OUT FOR DUCK DIAMETERS 6-18 M. (STN. INDIA - AUTUMN)
(EC 24A* 3SEP75)
EXCEEDANCE (%)
100
80
60
40
20
0
30
60
90
120
150
POWER IN KW/M

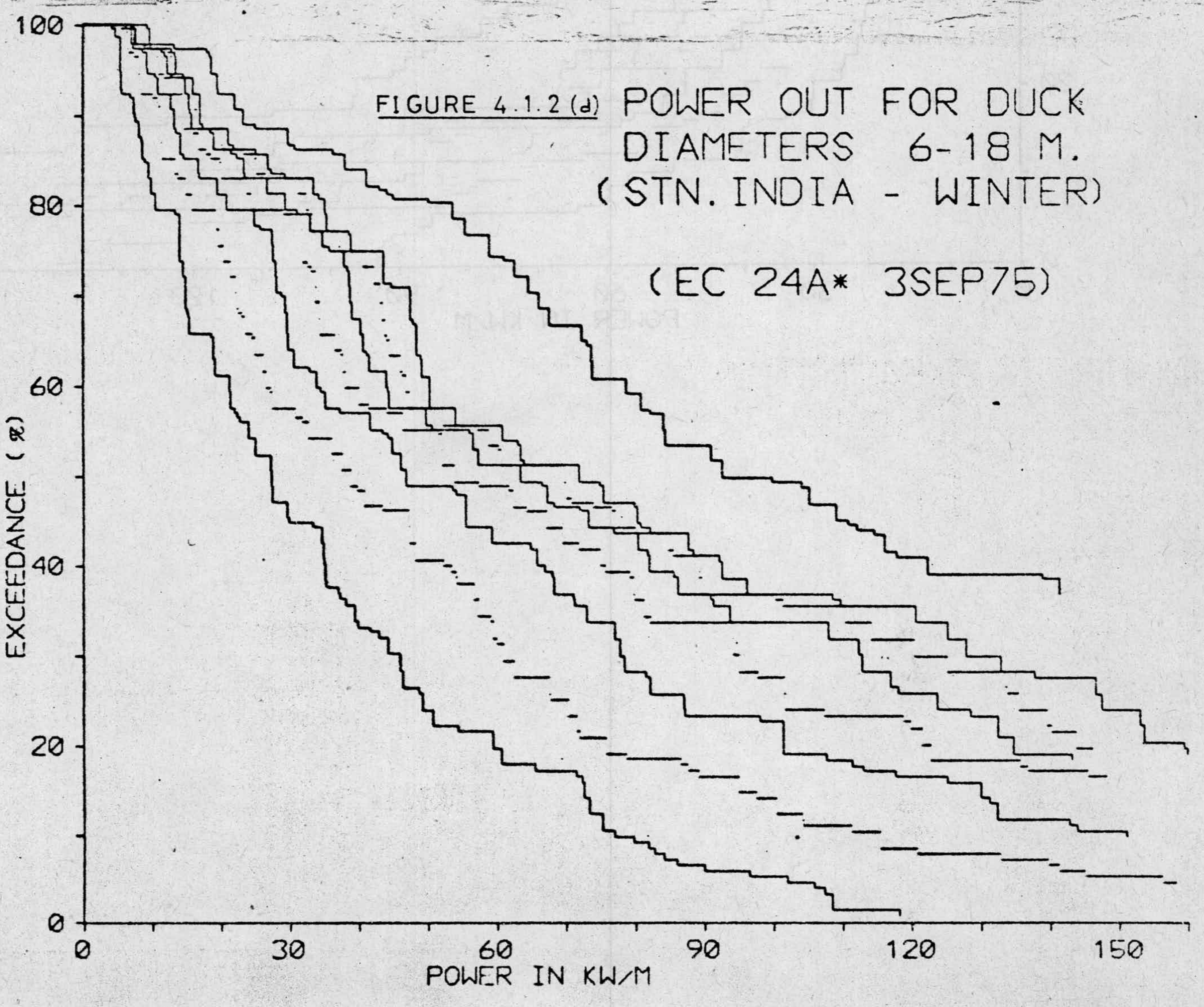


FIGURE 4.1.2(d) POWER OUT FOR DUCK DIAMETERS 6-18 M. (STN. INDIA - WINTER)
(EC 24A* 3SEP75)
EXCEEDANCE (%)
100
80
60
40
20
0
30
60
90
120
150
POWER IN KW/M

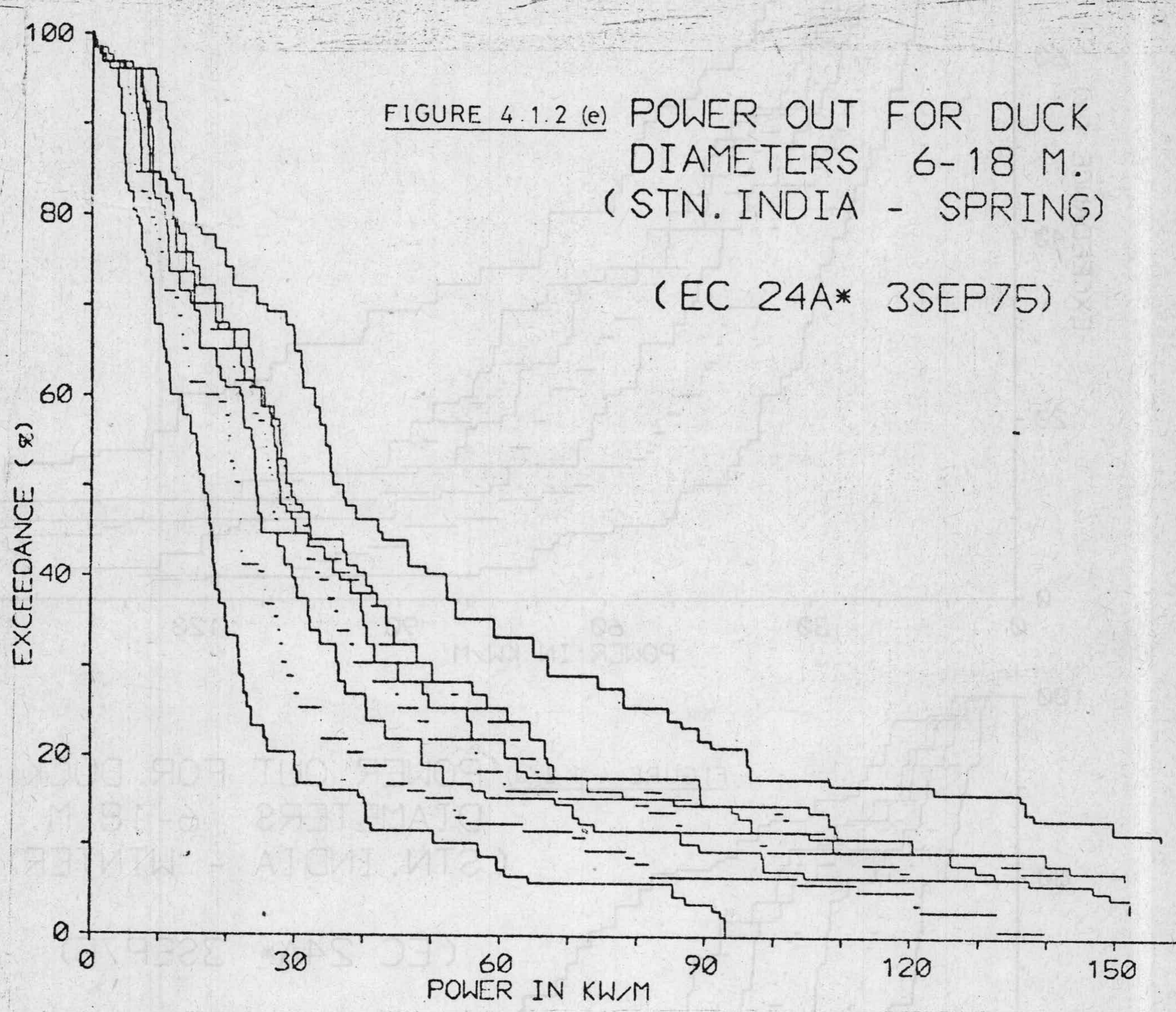


FIGURE 4.1.2 (e) POWER OUT FOR DUCK
DIAMETERS 6-18 M.
(STN. INDIA - SPRING)
(EC 24A* 3SEP75)
100
80
60
40
20
0
EXCEEDANCE (%)
0
30
60
90
120
150
POWER IN KW/M

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